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Relative sea-level variability during the late Middle Pleistocene: New evidence from eastern England



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ABSTRACT

Unravelling patterns of relative sea-level change during previous interglacials enhances our understanding of ice sheet response to changing climate. Temperate-latitude estuarine environments have the potential to preserve continuous records of relative sea level from previous interglacial (warm) periods. This is important because, currently, we typically only have snapshots of sea-level highstands from low-latitude corals and raised palaeoshoreline indicators while the (continuous) deep-sea oxygen isotope record only provides indirect evidence of sea-level changes. Here, we focus on the Nar Valley in eastern England, in which is preserved evidence of a late middle-Pleistocene marine transgression more than 20 vertical metres in extent. By applying a model of coastal succession and sea-level tendencies, as used in Holocene sea-level studies, we assess the mode (abrupt versus gradual) of sea-level change recorded by the interglacial Nar Valley sequences. Compiled palaeo-stratigraphic evidence comprising foraminifera, pollen and amino acid racemization dating, suggests that the mode of sea-level change in the Nar Valley interglacial sequence was gradual, with potentially two phases of regional transgression and relative sea-level rise occurring at two separate times. The first phase occurred during the latter part of marine Oxygen Isotope Stage (MIS) 11 from ~8 to 18 m OD; and, the second phase potentially occurred during early MIS 9 from ~3 to 3 m OD (with long-term tectonic uplift included in these estimates). We cannot conclusively preclude an alternative MIS 11 age for these lower sediments. The lack of indicators for rapid sea-level oscillations in the Nar Valley adds weight to an argument for steady melt of the ice sheets during both MIS 11 and 9.

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1. Introduction

To achieve an improved understanding of the relationship between climate, ice-sheet behaviour and sea level, we need to examine geological archives. Previous interglacials are often used to assess changes in past sea level during warm-climate episodes

(Dutton et al., 2015) and inform predictions of future sea-level change (Church et al., 2013; Lowe et al., 2009). A key component of this work is understanding how the ice sheets may respond to future climate change, which presents the largest uncertainty in future predictions (Grinsted et al., 2015). Reconstructing direct evidence of ice-sheet behaviour during previous interglacials is challenging, with many archives (e.g., proximal marine sediments and geomorphological features) removed by subsequent glaciations. Ice cores provide the best insight into past ice sheet accumulation (e.g., Dansgaard et al., 1993; Petit et al., 1999), but are typically drilled on stable ice domes in order to provide the most

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complete records, whereas the peripheries of ice sheets are the regions where mass is potentially lost during interglacial warming. As a result, observations of changes in past sea level are the most commonly used method to infer past ice-sheet changes (e.g., Dutton et al., 2015).

Evidence for modes of sea-level variability during MIS 11 and 9 is relative sparse, although they are interglacials of particular interest. MIS 11 is the longest interglacial of the late Quaternary (27 ka, Tzedakis et al., 2012) with global atmospheric CO₂ at 286 ppm, and is considered a potential analogue of the current interglacial due to similarities in orbital configuration (McManus et al., 2013). MIS 9, although comparatively short in duration (11.6 ka), is the warmest interglacial recorded in Antarctica, with global atmospheric CO₂ at 300 ppm (Past Interglacials working group of PAGES, 2016). Yin and Berger (2012) demonstrate that MIS 11c, MIS 9e and MIS 5e are the warmest interglacials of the last 800,000 years.

Evidence of MIS 11 and 9 sea level in low-latitude regions includes relict shorelines, marine terraces, tidal notches and coral reefs (e.g., Blakemore et al., 2015; Chen et al., 2014; Hearty and Kindler, 1995; Murray-Wallace, 2002; Raymo and Mitrovica, 2012; Schellmann and Radtke, 2004; Vezina et al., 1999). These features typically provide evidence for the elevation of the interglacial sea-level highstand at, or above present, although the calculated elevation is dependent on the assumed long-term uplift rate (e.g., Schellmann and Radtke, 2004). Based upon these relative sea-level (RSL) data, terrestrial ice extent during MIS 11 is assumed to be less than at present (Raymo and Mitrovica, 2012). However, little is known about stage MIS 9.

Marine oxygen isotope data can act as proxy for past sea level in the absence of coastal geomorphological features and the near-continuous time series may highlight any notable sea-level fluctuations (e.g., Siddall et al., 2007; Spratt and Lisiecki, 2016) (Fig. 1). These datasets suggest MIS 11 is typified by a single, long (~30 ka) duration highstand (Siddall et al., 2007). MIS 9 has a dominant single peak in sea level during the earliest substage (MIS 9e, Railsback et al., 2015), with a much smaller (~8–10 m lower) secondary peak during the next substage (MIS 9c) (Siddall et al., 2007). One or more sea-level oscillations during a highstand suggests dynamic behaviour of the ice sheets during the peak warm period with episodes of significant mass loss and gain, often in relatively short time intervals (a few thousand years or less), as has been reconstructed in MIS 5e (Kopp et al., 2009). The marine isotope records from MIS 11 and MIS 9 provide no evidence for abrupt, large scale oscillations in sea level that might be comparable to those seen in some MIS 5e records.

To achieve better understanding of the behaviour of ice sheets during MIS 11 and 9, there is a need for continuous records of RSL as

found in temperate-latitude estuarine environments, similar to detailed study of the MIS 5e Netherlands record (Long et al., 2015; Zagwijn, 1983). There is evidence for marine inundation in north-west Europe in MIS 11 and 9, for example within the Thames, and along the south and east coasts of England (Bridgland et al., 1999, 2013; Roe et al., 2009; Roe et al., 2011; Roe and Preece, 2011; Schreve et al., 2002; White et al., 2013). Flexure of the North Sea Basin, tectonic uplift/subsidence, sediment compaction and glacial-isostatic adjustment (GIA) during repeated glacial-interglacial cycles (Busschers et al., 2008; Lambeck et al., 2012; Rose, 2009) mean that the elevations at which sea-level positions are observed may be different from their elevations at the time of formation. Notwithstanding, these records are important because they are often continuous for all or part of the interglacial highstand(s), and, therefore, offer the potential to reconstruct the mode (gradual versus abrupt) of sea-level change with a high degree of precision, especially if microfossil analyses – as developed and applied in Holocene sea-level studies (e.g., Barlow et al., 2013) – can be applied.

The study area for this paper, the Nar Valley in eastern England (Fig. 2) has evidence of Pleistocene interglacial marine transgression(s), preserved over ~20 vertical metres (Stevens, 1959). By applying methodological insight gained from Holocene sea-level reconstructions in estuarine settings, similar to that discussed by Long et al. (2015), this paper aims to assess the mode of sea-level change during the interglacial Nar Valley record, which we demonstrate as recording marine inundation during MIS 11 and 9. This archive from a temperate-latitude location may increase our knowledge of ice-sheet behaviour during warm periods and aid predictions of future responses.

2. Identifying modes of sea-level change in estuarine sediments

Assessing the mode of sea-level change in estuarine sediments requires consideration of three main lines of evidence which have been applied extensively in temperate-latitude, estuarine-based studies of Holocene sea level:

1. The tendency of the sea-level indicator;
2. The nature of the transgressive or regressive contact, i.e., abrupt or gradual;
3. The lateral extent of the transgressive or regressive contact and its representation in adjacent vertically stacked sequences.

The tendency of a sea-level indicator describes the stratigraphic or morphological evidence for an increase (positive sea-level

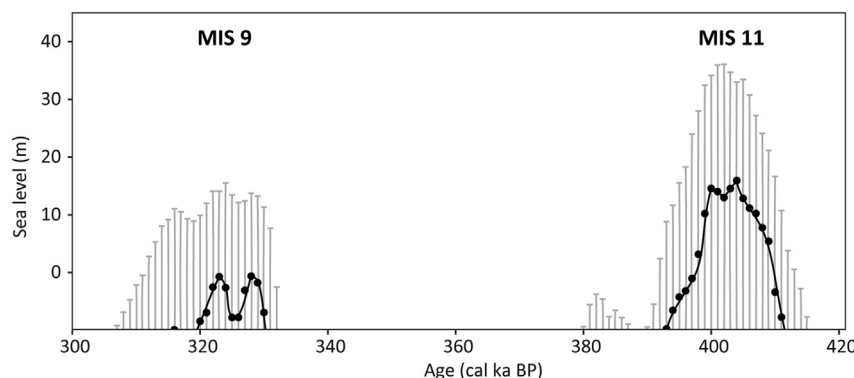


Fig. 1. MIS 9 and 11 global sea level highstands recorded by the Spratt and Lisiecki (2016) ocean core sea level stack (PC1) relative to present (0 m at 0 ka). Only vertical uncertainties shown, for clarity.

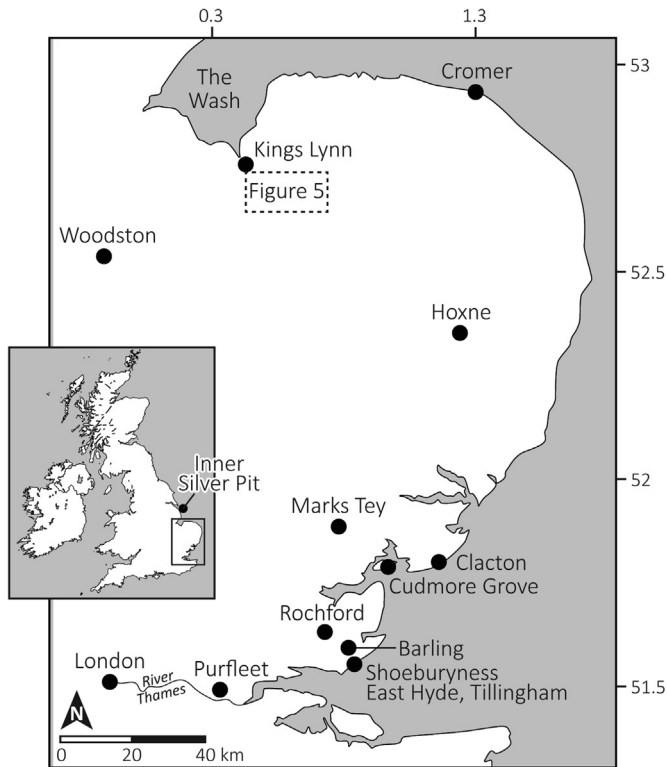


Fig. 2. Map of eastern England showing location of the Nar Valley (Fig. 5) and key locations given in text.

tendency) or decrease (negative sea-level tendency) in marine influence (Shennan et al., 2015; van de Plassche, 1986). This is a useful means of analysis as it goes beyond simply identifying the elevation of past sea level (as recorded by geomorphological indicators such as raised marine terraces or drowned shorelines), by also objectively describing changes in the height and salinity of the water table, which are in turn, related to the proximity of marine conditions and the elevation of the sample site with respect to defined tidal datums.

Tendency analysis requires litho-, bio- and chrono-stratigraphic data through a sequence of sediments, both laterally and vertically. Marine-brackish to brackish-freshwater vegetation successions in coastal lowlands of northwest Europe are typified by five coastal zones (Fig. 3), which reflect the tolerance of different species to the frequency of tidal inundation and groundwater salinity (after Waller et al., 1999). Gradual vertical changes in groundwater cause adjacent coastal vegetation zones to migrate up or down the environmental gradient. For example, when saline groundwaters rise, the coastal zones migrate landward so that salt marsh species (zone 3 in Fig. 3A) colonise former reed swamps (freshwater swamps colonised by the common reed) (zone 2). Microflora and fauna such as diatoms and foraminifera also exhibit zonation in the coastal zone (Fig. 3). Foraminifera are absent above the highest astronomical tides (HAT), but below this, specific assemblages dominate each coastal zone; for example *Jadammina macrescens* in the upper salt marsh, *Miliammina fusca* in the low marsh and tidal flats and *Elphidium excavatum* in sub-tidal environments (Murray, 2006). The zonation and succession of flora and fauna thus aid interpretation of the positive and negative tendencies of sea level within palaeo-estuarine sequences.

Litho- and biostratigraphical analysis of estuarine sequences may be also used to assess whether the transgressive or regressive contact, which records the up-core transition from fresh or

brackish-water to marine conditions (or vice versa), is abrupt or gradual (e.g., Long and Shennan, 1994). Abrupt changes in groundwater levels result in one vegetation/coastal zone being replaced by a non-adjacent vegetation type; for example a rapid sea-level rise may mean subtidal environments (zone 5 in Fig. 3A) replacing a freshwater swamp (zones 1 or 2), missing out the intervening salt marsh and tidal flat zones (zones 3 and 4). Fig. 3B shows two hypothetical stratigraphic sequences that would indicate a positive tendency, but with the second profile highlighting a potential jump in sea level with the typical pathway of coastal succession abruptly interrupted. This analysis is first done in a single core (as in Fig. 3B), and then may be considered together in a series of cores from across a site or region.

By tracing the timing and lateral and vertical extent of any transgressive or regressive contacts, it is possible to assess whether they record site-specific processes or are part of system-wide (i.e., estuary-scale) changes. Transgressive contacts from the same time period, which are recorded in multiple sites within one or more systems, may suggest a regional change in tendency, most likely caused by a rise in regional sea level, as opposed to local shifts in shoreline position caused by, for example, changes in sediment supply or tidal channel position (e.g., Shennan, 1982; Shennan et al., 2015; Tooley, 1982). Similarly, a salt marsh to intertidal mud transgressive contact recorded in one core may also be replicated in an adjacent vertically deeper sequence by subtidal sediments replacing intertidal muds. If a core does not record a switch from one environment to another, and simply contains either freshwater or marine sediments, it cannot record a change in tendency, but it may be used as a freshwater or marine limiting point, indicating that sea level must either have been below or above this elevation, respectively. Long and Shennan (1994) applied the tendency framework and models of vegetation and coastal succession to test for abrupt versus gradual positive and negative sea-level tendencies in both tectonically active and stable Holocene coastal settings. Here, we apply this approach to previous interglacial estuarine sequences, found in the Nar Valley.

3. The Nar Valley, eastern England

The Nar Valley (in Norfolk, eastern England) is an asymmetrical valley cut into underlying Mesozoic rocks (Fig. 4). The Pleistocene valley-fill is characterized by a glacial diamicton overlain by proglacial lake laminated clays (Gibbard et al., 1992; Ventris, 1996), most likely formed following retreat of the Anglian (MIS 12) ice sheet (Pawley et al., 2008). The clay facies are overlain by sands that fine upwards into clays that are, in turn, capped by a dense, lignitic bed of wood peat (Ventris, 1996). The sequence is collectively known as the Nar Valley Freshwater Beds (Stevens, 1959). Above these freshwater sediments in several locations is the Nar Valley Clay, often containing visible remains of marine fauna including foraminifera (Baden-Powell, 1967; Rose, 1835; Stevens, 1959). This paper focuses on the nature of this flooding surface, where marine sediments of the Nar Valley Clay transgress the lower freshwater deposits. In many locations the Nar Valley Clay is overlain by cold-stage outwash (the Tottenhill Sands and Gravels), with Holocene alluvial sediments filling the modern River Nar valley. Between the outwash fan formed by the Tottenhill Sands and Gravels (Gibbard et al., 1992, 2009; Lewis and Rose, 1991) and the modern Nar valley floor is a staircase of Middle–Late Pleistocene river terraces that testify to long-term land uplift (Boreham et al., 2010).

Previous pollen analyses through the Nar Valley Freshwater Beds clearly show affinities with the British Hoxnian interglacial pollen assemblage (Table 1), based upon the presence of the palynomorph ‘Type X’, high presence of *Hippophae* and the occurrence of significant frequencies of *Tilia* and *Taxus*, with the marine

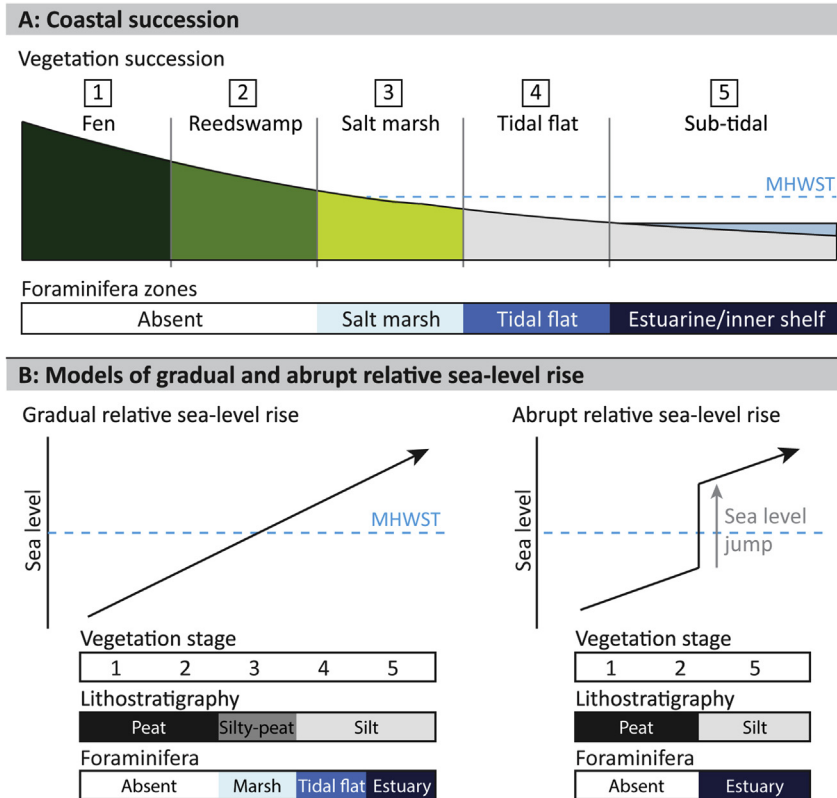


Fig. 3. A: Model of northwest European coastal succession (after Waller et al., 1999). B: Models of gradual (left) and abrupt (right) sea level rise as recorded by a coastal sequence (adapted after Long and Shennan, 1994). Note: the length of panel B is not indicative of the amount of sedimentation and both models assume the same total RSL rise.

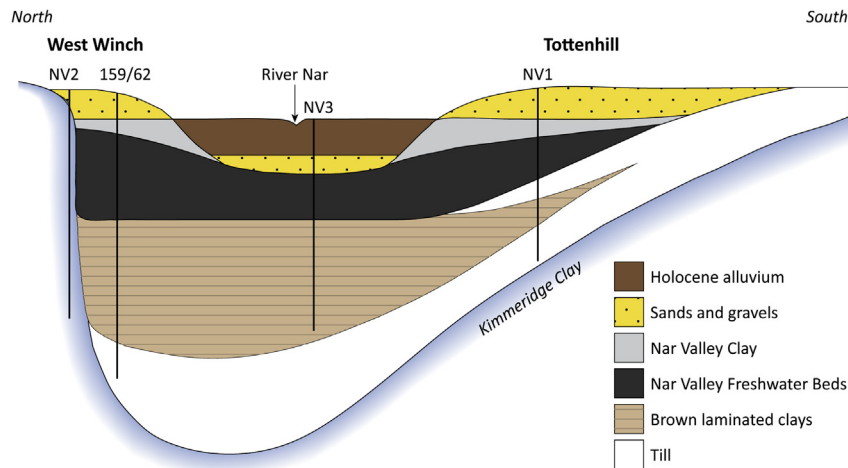


Fig. 4. Stratigraphy of the Nar Valley and locations of former boreholes. Cross section adapted from Ventris (1996).

transgression proposed to occur through early to late-temperate pollen stages Hollc to Hollb (Stevens, 1959; Ventris, 1996). However, northwest European 'Hoxnian' profiles are thought to characterise both MIS 11 and 9 (Thomas, 2001). Numerical and relative dating of the Hoxnian stratotype at Hoxne, Suffolk (Ashton et al., 2008) and the most complete Hoxnian pollen record at Marks Tey (Rowe et al., 1999; Turner, 1970) correlate the Hoxnian *sensu stricto* with the first warm period after MIS 12, therefore MIS 11 (Candy et al., 2014). However, the evident similarities between the MIS 11 and 9 pollen assemblages means that separating sequences solely based upon pollen spectra is a challenge (Roe et al., 2009),

and no single vegetation zone can be considered sufficiently diagnostic to be applied for dating interglacial periods. Numerical dating of the freshwater peat at Tottenhill by $^{230}\text{Th}/^{238}\text{U}$ produced a mean age of 317 ± 14 ka (Rowe et al., 1997), whilst multiple isoleucine epimerization determinations of *Ammonia beccarii* and *Aubignyna perlucida* foraminifera within the Nar Valley Clay yield mean A/I values of 0.135 and 0.111 respectively (Scourse et al., 1999), all of which suggested that the Nar Valley Clay correlated with MIS 9. By comparison, similar aminostratigraphic dating of a Hoxnian-type sequence in the Inner Silver Pit area of the southern North Sea produced ages which suggest its deposition during MIS

Table 1

Summary of Hoxnian-type pollen assemblage characteristics and stages at Hoxne and Marks Tey (Turner, 1970; West, 1956).

Zone name	Pollen stage	Fossil pollen assemblage characteristics at Marks Tey and Hoxne
Post temperate	HolV	The Early-Glacial. Arctic/Sub-Arctic conditions. Non-arboreal pollen (NAP) increases.
Late Temperate	HolIII a&b	Masked by <i>Alnus</i> at Hoxne, <i>Azolla filiculoides</i> present. Gradual increase in <i>Pinus</i> and <i>Picea</i> , followed by increases in <i>Abies</i> and <i>Carpinus</i> in IIIa at Marks Tey, which is particularly dominant in HolIIIb (with <i>Alnus</i>). Declines of <i>Quercus</i> and <i>Ulmus</i> in IIIa while <i>Corylus</i> remains. <i>Ilex</i> , <i>Hedera</i> and <i>Taxus</i> present.
Early Temperate	HolId	<i>Alnus-Quercus-Ulmus-Tilia</i> . Mixed oak forest with expansion of <i>Ulmus</i> and decline of <i>Tilia</i> . <i>Fraxinus</i> also present.
	HolIc	<i>Alnus-Quercus-Betula-Tilia</i> . Rapid expansion of <i>Alnus</i> .
	HolIb	<i>Betula-Quercus-Pinus</i> . <i>Quercus</i> became dominant. <i>Ulmus</i> incoming with sparse <i>Tilia</i> , <i>Alnus</i> and <i>Picea</i> later
	HolIIa	<i>Betula-Pinus</i> colonising. Evidence of <i>Quercus</i> arriving.
Pre-temperate/ Lateglacial	Hol	<i>Hippophae</i> scrub, some <i>Betula</i>

11 (Scourse et al., 1998), highlighting the challenge of ascribing a definitive MIS age for Hoxnian pollen-type sequences within the same region (Scourse et al., 1999).

Numerical dating of the Nar Valley has not been applied outside of the Tottenhill site. We therefore use amino acid racemization dating (AAR) of *Bithynia tentaculata* opercula collected from the Nar Valley Freshwater Beds with comparison to the established British Quaternary chronological framework (Penkman et al., 2011, 2013), in an effort to constrain the marine Oxygen Isotope Stage(s) during which the freshwater deposits were emplaced. However, the current absence of an AAR chronological framework for late-Quaternary marine sediments in Britain means we cannot independently date the Nar Valley Clay itself, and are therefore reliant on correlation with the Hoxnian pollen assemblages in Table 1.

4. Methods

4.1. Field methods

Our field strategy was guided by previous work (Gibbard et al., 1992; Stevens, 1959; Ventris, 1996), with resampling near to known Nar Valley Clay sequences where access was available. We aimed to sample material across a range of elevations to provide as much information as possible regarding the lateral and vertical extent of the marine sediments.

Material was collected from five locations (Figs. 5 and 6, grid references provided in the results, section 5): (1) at the lowest part of the working Blackborough End Quarry, near to the Blackborough End sequence described by Stevens (1959); (2) a newly exposed section at the southern end of Tottenhill Quarry south of the previously described sections (Gibbard et al., 1992; Ventris, 1996); (3) Horse Fen, aiming to replicate the work by Stevens (1959); (4) Railway Cottage, east of East Winch near to Stevens' (1959) boreholes 1–3; and (5) Bradmoor Hill at Little Long Plantation ~1 km east of Summer End Farm (Stevens, 1959). Cores at Blackborough End Quarry, Horse Fen, Railway Cottage and Bradmoor Hill were collected in 2012 using a Percussion drilling kit and window sampler. At Horse Fen a second deeper core was collected in 2013 using a shell and auger drilling rig, ~50 m north of the first core to collect material below the wood peat. A newly opened face (2014) at Tottenhill Quarry, where the overburden Tottenhill Sands and Gravels had been excavated, provided access to the Nar Valley Freshwater beds and overlying clay for monolith sampling. All boreholes were levelled to metres Ordnance Datum (m OD) using local benchmarks (with the exception of Tottenhill Quarry where the elevation had to be estimated from Ventris, 1996) with the latitude and longitude taken using a handheld GPS. The attitudinally lowest occurrence of Nar Valley Clay is found at Manor Farm (Fig. 6), but we were unable to resample this site due to access restrictions, and therefore are reliant on the results of Mitlehner (1992).

4.2. Laboratory methods

Following fieldwork, the collected sediment was wrapped in plastic and stored in a fridge (~4 °C) at Durham University and sampled for further analysis. The sampling interval of the cores varied according to the stratigraphy and avoided core breaks, with a higher resolution sampling interval across the peat-clay contacts. Organic content was measured across the peat-clay contact in the six cores, as percentage loss on ignition (LOI), by burning ~2–5 g of dried sediment at 550 °C for four hours.

All cores were subjected to spot-sampling to establish in the first instance, the absence or presence of foraminifera. Where foraminifera were found, full counts and identification of taxa were carried out and absolute concentrations calculated. Samples (0.4–7 cc) were wet-sieved and the fraction 63–500 µm retained. The samples were divided into four at least once and, a fraction expected to yield at least 100 specimens of the sample was picked. Some samples had too few foraminifera to provide a useful count. On average, ~140 specimens were counted per sample. The foraminifera were identified to species level based on the taxonomy according to Loeblich and Tappan (1987), Murray (1979); Murray et al. (2000) and Walton and Sloan (1990). We follow Walton and Sloan (1990) for the genus *Ammonia* because we recognise their forms in our samples, but we are aware of the genetic debate and different nomenclature (Hayward et al., 2004). Diatom samples were also prepared across each peat-clay contact, but no diatoms were preserved.

Pollen analysis was undertaken on 2 cm³ sub-samples at 16, 8, 2 or 1 cm resolution from the five cores (due to limited material for analysis the analysed depths are not the same as for foraminifera samples). Higher resolution sampling focussed on the peat sections of the cores and transitions from peat to clay. Standard pollen extraction techniques were used (Moore et al., 1991). Because pollen was sparse in many samples, micromesh sieving (10 µm) was used to remove the clay and finest silt fraction prior to extraction. For Blackborough End Quarry, Tottenhill and Railway Cottage, samples were then combined with heavy liquid (LST Fassetfloat) prepared to a density of 1.9 g/ml, and centrifuged for 20 min at 1800 rpm (Nakagawa et al., 1998). The retained pollen was, in all cases, mounted on microscope slides in glycerol jelly. Where the density separation process was used, all residues were examined and found to contain no discernible pollen grains. The pollen sum counted was dependent upon pollen preservation between sites and within site. In general, a minimum sum of 300 land pollen grains was aimed for. Pollen taxa were identified using the keys in Moore et al. (1991) and an extensive comparative collection was available to aid identification of critical taxa. In general, the taxonomy of Moore et al. (1991) modified by Bennett (1994) has been used. Percentage calculations were based on the sum of the dry land pollen with pollen marsh and aquatic pollen as a percentage of

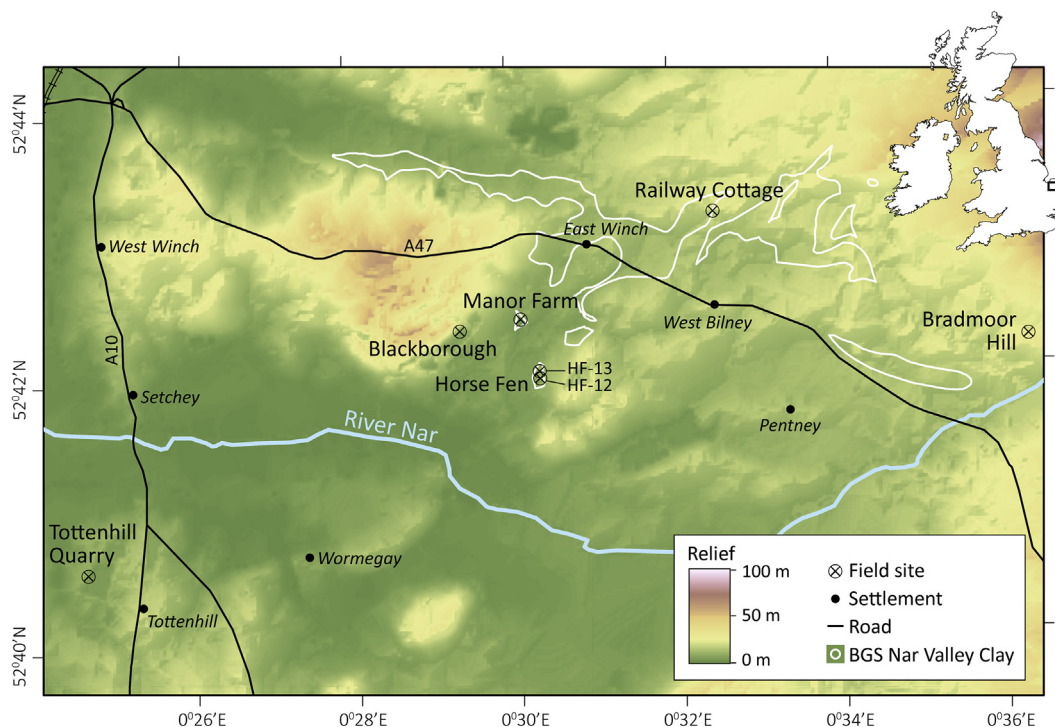


Fig. 5. Map of the Nar Valley showing locations of new boreholes and key settlements. Topography from NEXTMap British Digital Terrain Model Dataset produced by Intermap with tickmarks in degrees, minutes and second. White contours show location of Nar Valley Clay as mapped by British Geological Survey (BGS).

the sum plus this category. This also applies to fern spores and to the miscellaneous (pre-Quaternary palynomorphs, Dinoflagellates and *Pediastrum*).

The current technique of amino acid analysis developed for geochronological purposes (Penkman et al., 2008) combines a reverse-phase high-pressure liquid chromatography (RP-HPLC) method of analysis (Kaufman and Manley, 1998) with the isolation of an 'intra-crystalline' fraction of amino acids by bleach treatment (Sykes et al., 1995). This combination of techniques results in the analysis of D/L values of multiple amino acids from the chemically protected (closed system) protein within the biomineral, thereby enabling both decreased sample sizes and increased reliability of the analysis. Amino acid data obtained from the intra-crystalline fraction of the calcitic *Bithynia* opercula indicate that this biomineral is a particularly robust repository for the original protein (Penkman et al., 2011, 2013) and therefore has been targeted in this study.

Amino acid racemization (AAR) analyses were undertaken on samples detailed below (supplementary information for results). Opercula were not found in the freshwater sediments in any other cores.

- 3 individual *Bithynia tentaculata* opercula from Nar Valley Freshwater Beds, from a grab sample of peat near to the Tottenhill analysed section (as in Fig. 6), that had undergone mineral diagenesis, appearing chalky (NEaar 9786–9788; THBto1–3).
- 3 individual *Bithynia tentaculata* opercula, from the same grab sample of peat as the chalky opercula near to the Tottenhill section, that had not undergone mineral diagenesis (NEaar 9789–9791; THBto4–6);
- 6 individual *Bithynia tentaculata* opercula from the shelly peat at the base of the analysed Tottenhill section (NEaar 10337–10342; Tott3Bto1–6) (see results, location given on Fig. 9);

- 1 incomplete fragment of *Bithynia tentaculata* operculum from Horse Fen, HF13, 1058–9 (NEaar 10344; HF13Bo1) (see results, location given on Fig. 7).

All samples were prepared using the procedures of Penkman et al. (2008) to isolate the intra-crystalline protein by bleaching. Two subsamples were then taken from each shell; one fraction was directly demineralised and the free amino acids analysed (referred to as the 'free' amino acids, FAA, F), and the second was treated to release the peptide-bound amino acids, thus yielding the 'total' amino acid concentration, referred to as the 'total hydrolysable amino acid fraction' (THAA, H*). Samples were analysed in duplicate by RP-HPLC, with standards and blanks run alongside samples. During preparative hydrolysis, both asparagine and glutamine undergo rapid irreversible deamination to aspartic acid and glutamic acid respectively (Hill, 1965). It is, therefore, not possible to distinguish between the acidic amino acids and their derivatives and they are reported together as Asx and Glx respectively.

5. Results

Six new boreholes and one quarry face section in the Nar Valley reveal shell-bearing clay (containing *Hydrobia*, *Littorina* and *Ostrea edulis*) up to +18 m OD. At Horse Fen, Blackborough Quarry and Tottenhill (the lower sites) the clay overlies a lignitic peat from ~2.5 to +3 m OD (Fig. 6). In comparison, in the upper sites, Railway Cottage and Bradmoor Hill, the shell-bearing clay overlies a dense, chalk-rich clay and medium to coarse sand rather than lignitic peat. Despite extensive coring using a hand gouge and auger at a number of test sites in the modern elevation range between the lower and upper sites, we found no evidence of sediments resembling the Nar Valley Clay or Nar Valley Freshwater Beds between +4 and +8 m OD, typically encountering bedrock Carstone under the shallow Holocene/Lateglacial substrate. It must be noted that Stevens

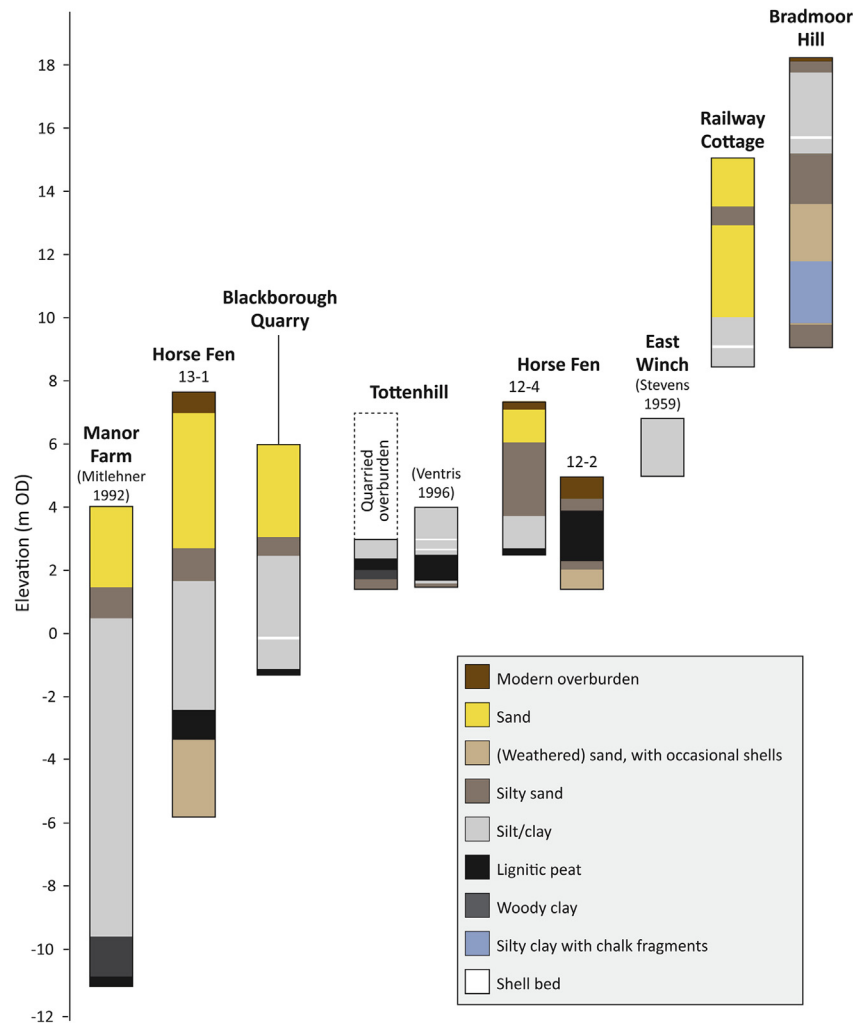


Fig. 6. Nar Valley borehole lithology, collected as part of this work, with additional boreholes from the literature at sites we were unable to resample. Elevation of Tottenhill section estimated from Ventris (1996).

(1959) documented Nar Valley Clay at ~5 m OD at a former brickyard near East Winch, so it is not clear whether the absence of these sediments within this vertical range is real or an artefact of the field sampling. We summarise the lithological and biostratigraphical results from each location in turn, from the lowest occurrence of the marine clay (Horse Fen 13-1) to the highest (Bradmoor Hill) (Fig. 6), with full biostratigraphy given in the supplementary information.

5.1. Horse Fen 13-1

Drilling at Horse Fen (52.70038, 0.50385), ~50 m north of the original Stevens (1959) investigations, revealed an organic-rich brown sandy silt from 11.00 to 11.50 m (Fig. 6), above which, is a dense, black, lignitic peat to 9.98 m, with occasional (up to ~0.05 m thick) layers of marl. The peat-clay boundary with the overlying stiff grey silty-clay at 9.98 m (−2.28 m OD) is visually sharp (<5 mm), with a decrease in organic content from ~80% at 10.05 m to ~5% at 9.90 m (Fig. 7). Due to water saturation, it was not possible to collect material for analysis from 8.44 to 9.89 m. The stiff grey clay contains occasional shells of *Littorina* and is overlain by yellow-orange sand from ~5 m to ~0.5 m below the surface.

Foraminifera were not found in the dense black peat, with the first occurrences in low numbers at 9.99 m. The first 0.04 m above

the peat-clay contact is dominated by forms of *Ammonia beccarii*, *Aubignyna perlucida*, *Elphidium williamsoni* and *Haynesina germanica* (Fig. 7). *E. williamsoni* and *E. incertum* decrease by 9.80 m, with *A. beccarii* f. *beccarii*, *H. germanica*, *Aubignyna perlucida* and *Elphidium incertum* dominant to 7.70 m with no marked changes in the assemblage. Samples at 6.70 m and 5.70 m show a decrease in forms of *A. beccarii* and an increase in *Elphidium gerthi* (supplementary information). These assemblages suggest an increase in water depth, as lower down it is dominated by intertidal species (e.g., forms of *A. beccarii*, *E. williamsoni*) which at the top of the sampled interval, is replaced by *E. gerthi*, which is found in fully marine environments (e.g., Knudsen, 1984).

There are a number of significant changes in the Horse Fen 13-1 pollen profile which are, in part, related to the changing stratigraphy of the site. Pollen preservation in the differing sediment facies is poor and especially in the lignitic peat from above 10.58 m. The basal zone (to 10.90 m) is dominated by *Betula* with few other trees and shrubs although, *Juniperus* and possible *Tsuga* are present. During this earliest phase, Poaceae and Cyperaceae are the dominant herbs and are probably autochthonous with other marsh taxa recorded (*Typha latifolia*, *Typha angustifolia*/Sparganium and *Menyanthes trifoliata*). At 10.91–10.93 m, there is clear evidence of a stratigraphic hiatus between the basal sandy silts and overlying peat. In the humic silt above the basal peat (10.90–10.70 m), *Pinus*

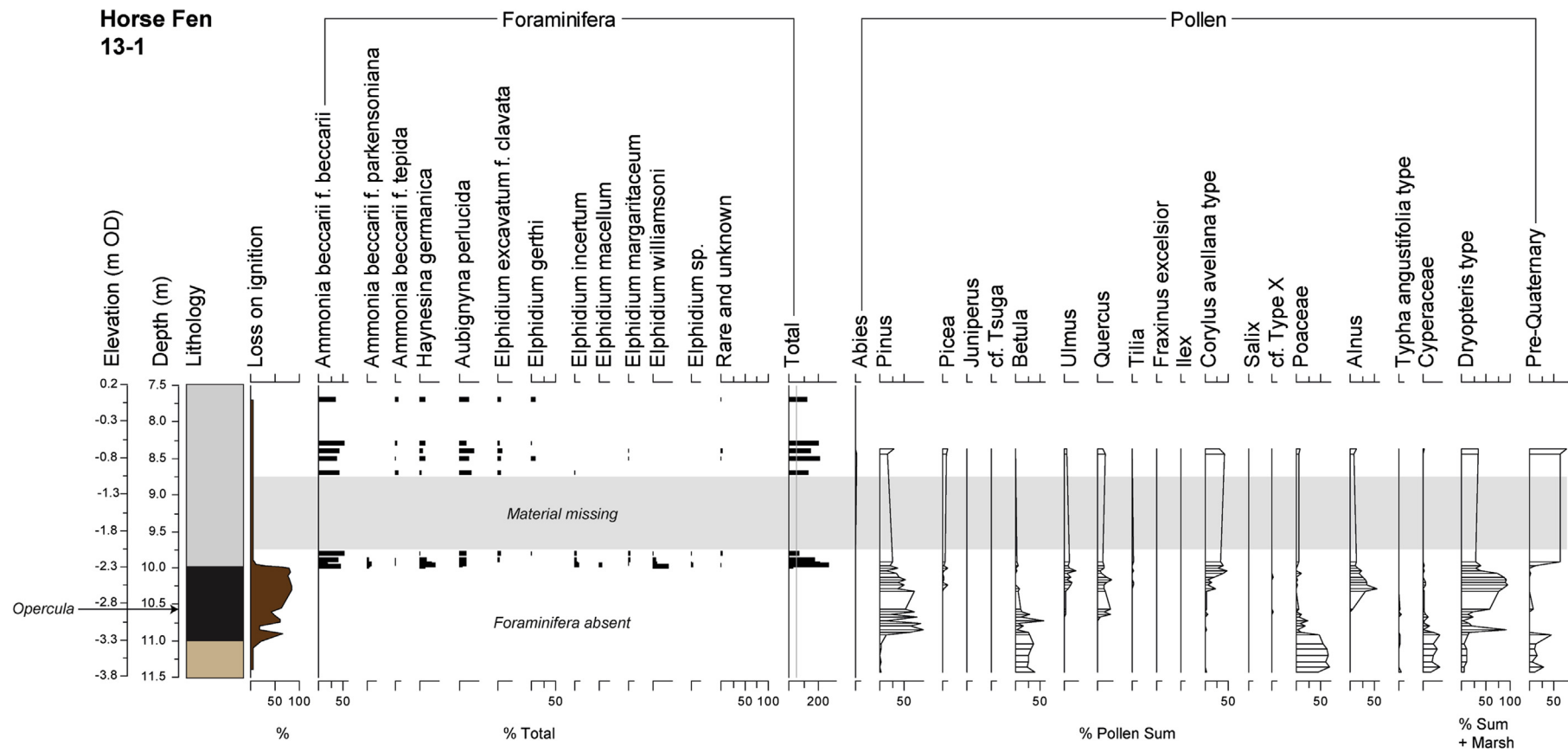


Fig. 7. Horse Fen 13-1 litho- and bio-stratigraphy. Foraminifera >5% of total tests counted (grey line n = 50). Selected pollen taxa shown. Lithology key same as Fig. 6.

Blackborough Quarry

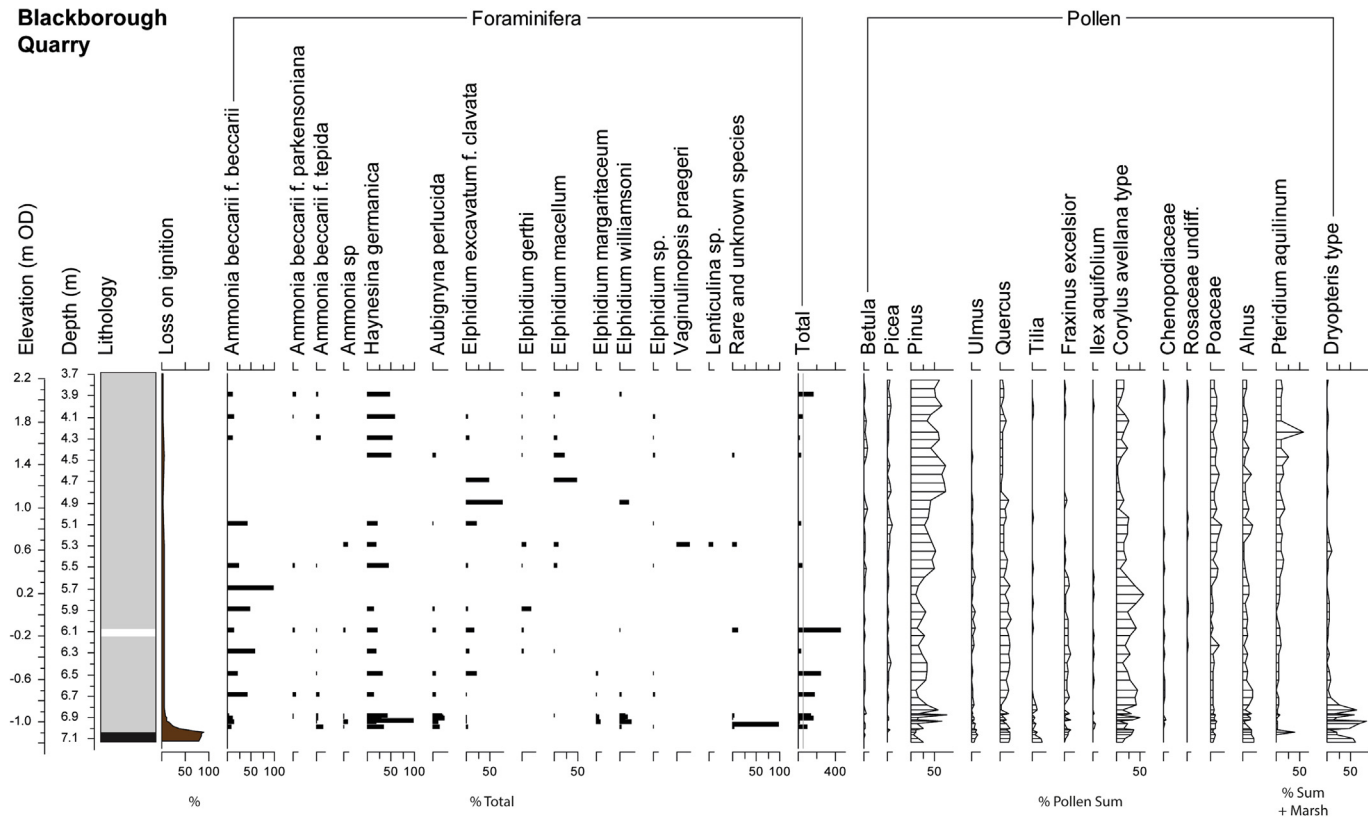


Fig. 8. Blackborough End Quarry litho- and bio-stratigraphy. Foraminifera >5% of total tests counted (grey line $n = 50$). Selected pollen taxa shown. Lithology key same as Fig. 6.

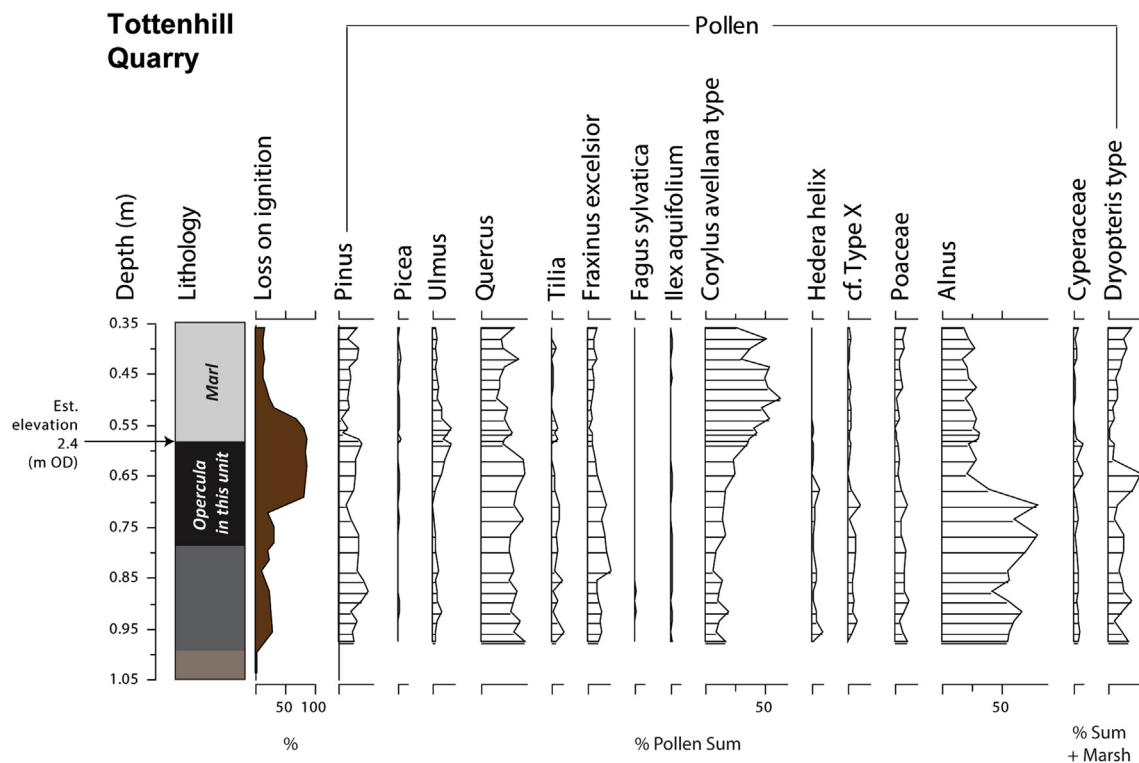


Fig. 9. Tottenham litho- and biostratigraphy. Selected pollen taxa shown. Lithology key same as Fig. 6. No foraminifera were found at this location.

becomes the dominant taxon with largely reduced values of *Betula*, Poaceae, Cyperaceae and pre-Quaternary palynomorphs. Subsequently, with change to the lignified peat, *Pinus* remains important but also with marked increases of thermophiles, that include *Ulmus*, *Quercus*, *Tilia*, *Fraxinus*, *Alnus* and *Corylus avellana* type. Values of these latter taxa become increasingly important towards the top of the profile, especially after the change to humic silt above 10.1 m. Throughout this period, levels of Poaceae and Cyperaceae remain low. Spores of Pteropsida (*Dryopteris* type) attain high levels, which reflect the drier ground flora of the site and also their differential preservation in the humified peat.

It is clear that the depositional habitat during peat formation was variable. Initially fluvial conditions pertained, manifested by substantial numbers of reworked pre-Quaternary palynomorphs, and the autochthonous vegetation was probably grass and sedge fen. There is a hiatus in the stratigraphy which may be due to erosion of sediment or cessation of accumulation (perhaps due to groundwater lowering), after which the depositional environment was of lower energy with deposition of humic silt again under fen vegetation. This progressed through to a drier alder carr habitat under which the lignified wood peat accumulated. There was a subsequent reversal to wetter, fluvial/alluvial conditions. The pollen sequence obtained is, unsurprisingly, similar to that obtained by Stevens (1959) and may be compared with the Hoxnian profile at Marks Tey (Turner, 1970). The base to 10.90 m may be correlated with pollen sub-zone Holla due to the importance of *Betula* and a diverse range of herb pollen. *Hippophae rhamnoides*, as with Stevens (1959), is not found. The subsequent arboreal development with expansion of *Pinus* above the hiatus, with the following increase of thermophiles, suggests a successional sequence of Holla (10.90–10.70 m), Hollb for 10.70–10.50 m and Hollc from 10.50 to 10.14 m. The top may also be Hollc or possibly, the early part of Holll, although this is not clear. The AAR result from a single operculum fragment from Horse Fen (at 10.58 m) is discussed in the chronology results section below, though the sample size is too small to be reliable.

5.2. Blackborough End Quarry

The Blackborough End Quarry borehole (52.70565, 0.48763) is the lowest elevation site sampled in the modern Nar Valley, although the peat-clay contact is 1.18 m higher than at Horse Fen 13-1. A hard, black, lignitic peat with organic content of ~85% (Fig. 8) extends from the base of our core at 7.15 to 7.06 m (upper peat contact at -1.1 m OD), with a visually sharp contact to the overlying silt-clay (Fig. 6). At 0.08 m above the peat-clay contact is a silty-clay with detrital peat and unidentified shell fragments. Above this the organic content decreases to ~10% and the dark grey sandy silt, with occasional *Littorina* and a shell bed of *Ostrea edulis* at 6.05–6.15 m, extends up to 3.35 m below the surface. Iron-stained grey-brown silty sand overlies the sequence.

Foraminiferal preservation in the Blackborough End Quarry core is variable. No tests were found below 7.00 m; at this level, the assemblage is dominated by forms of *A. beccarii*, *A. perlucida*, *E. williamsoni* and *H. germanica* (Fig. 8). Counts then remain low until 6.92 m where the silt-clay to 6.10 m primarily contains forms of *A. beccarii*, *E. excavatum* f. *clavata* and *H. germanica*. Above this, to 3.70 m, preservation is again poor, albeit with an assemblage of forms of *A. beccarii*, *Elphidium* spp and *H. germanica*. This fairly homogeneous, subtidal assemblage, contains two samples containing foraminifera indicative of deeper water; at 6.10 m a number of *Eggerelloides scaber* are found (although only 4%, so in the “rare and unknown” category), and a few *Gavelinopsis praegeri* at 5.30 m. The presence of these sub-tidal species (e.g., Alejo et al., 1999; Alve and Murray, 1999; Mendes et al., 2004) in discreet intervals may

indicate storm events.

The pollen sequence from Blackborough End Quarry represents an early-temperate woodland with thermophiles including *Ulmus*, *Quercus*, *Tilia*, *Fraxinus*, *Ilex* and *Hedera* which are present to the base of the profile (Fig. 8), potentially correlating with Holl. These taxa then decline over the peat-clay transition with an increase in coniferales (*Pinus*, *Picea*) which may be viewed as transition to early Holll. It must be noted that diagnostic Hoxnian-type taxa such as Type X, *Taxus*, *Vitis*, low levels of *Carpinus* and the lack of *Abies* (typical of mid Holll) are not evident which means that the correlation with the Hoxnian pollen stages (Table 1) is tentative. The fluctuating nature of the pollen assemblages across the peat-clay transition at ~7 m may be partly taphonomic due to poor pollen preservation (indicated by very damaged pollen, low pollen concentration and, in particular, by substantial numbers of *Pteropsida* spores), or may indicate a hiatus in the record and may also explain the lack of diagnostic Hoxnian taxa. It is also possible that the peat deposits may have accumulated over a long period of time, whilst the clay above represents a much more rapidly accumulating sediment.

5.3. Tottenhill

A newly-opened section at the south-west corner of Tottenhill Quarry (52.66985, 0.40428), ~0.8 km south of locations Ta-Tf of Ventris (1996), provided an opportunity to observe the lateral extent of the Nar Valley peat and its stratigraphic relationship to the overlying sediment. Coarse-to-fine sands and gravels had been excavated from above the section, leaving a truncated surface over the underlying ~1.6 m section. The basal unit at the sampled section is a light-grey silty sand with occasional shells (below which, in some other locations, a sticky light-grey silty clay with chalk clasts was observed). The silty-sand is replaced by 0.21 m of grey-brown organic enriched clay-silt which then grades into a brown-black, dense woody peat for another 0.21 m (Fig. 6). The peat has a reasonably sharp (<1–5 mm) upper contact (estimated elevation 2.4 m OD, based upon the Ventris (1996) stratigraphic sections Ta-Tf) with the overlying ~0.5 m of brown-grey silty clay, which contains many visible shells, sometimes in laminated bands. The organic content decreases across the peat-clay contact from ~85% to 14% (Fig. 9). No foraminifera were found in the peat and overlying clay.

The Tottenhill Quarry pollen sequence (Fig. 9) presented in this study is truncated by the recent quarry excavations and, therefore, we also consider the profile from Ventris (1996) for a more complete picture. The sequence represents a temperate wooded environment dominated by deciduous taxa such as *Alnus*, *Quercus* and *Ulmus*; that is, diagnostic of an early temperate interglacial phase. Thermophiles present include, *Alnus*, *Tilia* and *Hedera*, as well as Type X (Phillips, 1974; Turner, 1970) and are typical of this phase and, the pollen sequence corresponds most closely with Hollb, moving into Hollc (West, 1980). The high *Alnus* values followed by a rise and fall in *Corylus* values, as well as a rise and fall in *Ulmus* levels, are characteristic of this transition. The results of the AAR analysis of the opercula found at Tottenhill are presented in section 5.7.

5.4. Horse Fen 12-2 and 12-4

Cores 12-2 and 12-4 at Horse Fen (Fig. 6) were collected to provide foraminiferal data in association with the Stevens (1959) pollen diagram obtained from this site. Core 12-2 (52.69946, 0.50387) is located in a small clay pit where the overburden material had been removed; core 12-4 (52.69959, 0.50388) is ~10 m north on a track above the pit. We include 12-2 in Fig. 6 for

completeness as it is geographically closest to Stevens' Horse Fen pollen diagram. We are, however, cautious of potential erosion/disturbance of the peat-clay transition (see below) and therefore focus our investigations on borehole 12-4 where there is a greater thickness of clay for analysis. The base of core 12-4 contains a grey-black, very compacted peat from 4.69 to 4.52 m, with an upper contact (at 2.64 m OD) to the overlying grey sandy silt with occasional shells and a particularly shell-rich layer containing fragments of *Ostrea edulis* at 4.27–4.35 m. The organic content decreases from ~80% at 4.54 m to ~4% at 4.50 m (Fig. 10). The grey sandy silt extends to 3.40 m, above which is ~0.80 m of light brown clay with some organics, overtopped by orange-grey silty sand from 2.60 to 0.20 m.

Foraminifera occur between 4.54 and 2.25 m in Horse Fen 12-4, with forms of *A. beccarii* being dominant, and associated with *H. germanica*, *A. perlucida*, *E. excavatum* f. *clavata*, *E. macellum*, and *E. williamsoni* (Fig. 10). There is a subtle assemblage change from an intertidal assemblage with *Ammonia* spp. at 4.54 m, to a shallow sub-tidal assemblage with *E. macellum* (e.g., Li et al., 2000) between 4.41 and 2.65 m, reinforced by a peak in *E. gerthi* at 3.05 m. Between 3.05 m and 2.25 m this trend reverses. A similar assemblage of forms of *A. beccarii*, *A. perlucida* and *H. germanica* is found above the peat in core 12-2. (Foraminifera counts from 12 to 2 are presented in the supplementary information).

Stevens (1959) divides her Horse Fen peat pollen profile into two parts: a lower non-arboreal pollen zone dominated by Cyperaceae with small quantities of *Betula* and *Pinus*, followed by gradual arrival of a mixed oak forest, though heavily dominated by *Alnus*. Stevens suggests the profile likely records a sedge fen around a lake (a fen is a minerotrophic peatland common in modern Eastern England) that was later overgrown by an alder carr, most likely equivalent to successions from Holla/b to Holld (West, 1980). Above

the peat-clay contact *Pinus* dominates with low levels of *Picea*, although the original Stevens profile is truncated ~0.2 m above the top of the peat, which fits with our borehole investigations at core 12-2.

5.5. Railway Cottage

The Railway Cottage borehole (52.71964, 0.54043) is ~200 m west of Stevens' (1959) boreholes 1–3 where she shows the Nar Valley Clay thinning out along a ridge, at ~15–16.5 m OD. The base of our borehole (6.51 m) stopped in flints/stones (Fig. 6) which we also observed in the base of a drainage pit on the other side of the road to our core. From the base (8.51 m OD) to ~4.9 m is a black-grey silty clay containing remains of shells, including a visible band at 5.81–5.86 m, most likely *Ostrea edulis*. The organic content of the clay is low (<9%). Above the clay is ~4.9 m of coarse sand with occasional flints that extend to the surface.

Foraminifera are present from the base of the sample core (6.46 m) to 5.30 m, above which, no tests occur (Fig. 11). A relatively homogeneous assemblage, dominated by forms of *A. beccarii*, *A. perlucida*, *H. germanica* and *E. incertum*, characterises this lower ~1.2 m of the silty clay. The only notable change in this assemblage is a shift from *A. beccarii* f. *tepida* to *A. beccarii* f. *parkensoniana* towards the top of the clay, which may be indicative of higher salinities (Debenay et al., 1998; Walton and Sloan, 1990).

The pollen sequence at Railway Cottage (Fig. 11) represents a late-temperate interglacial stage attributed to HolIII, possible the very end of HolIIIa to HolIIIb (West, 1980). Thermophilous taxa and components of the deciduous, oak-dominated woodland (*Quercus*, *Ulmus*, *Hedera* and *Ilex*) decline or, are absent, above 6.00 m, suggesting climatic deterioration. The rapid expansion of *Abies* pollen above 6.10 m has suppressed the within sum percentages of the

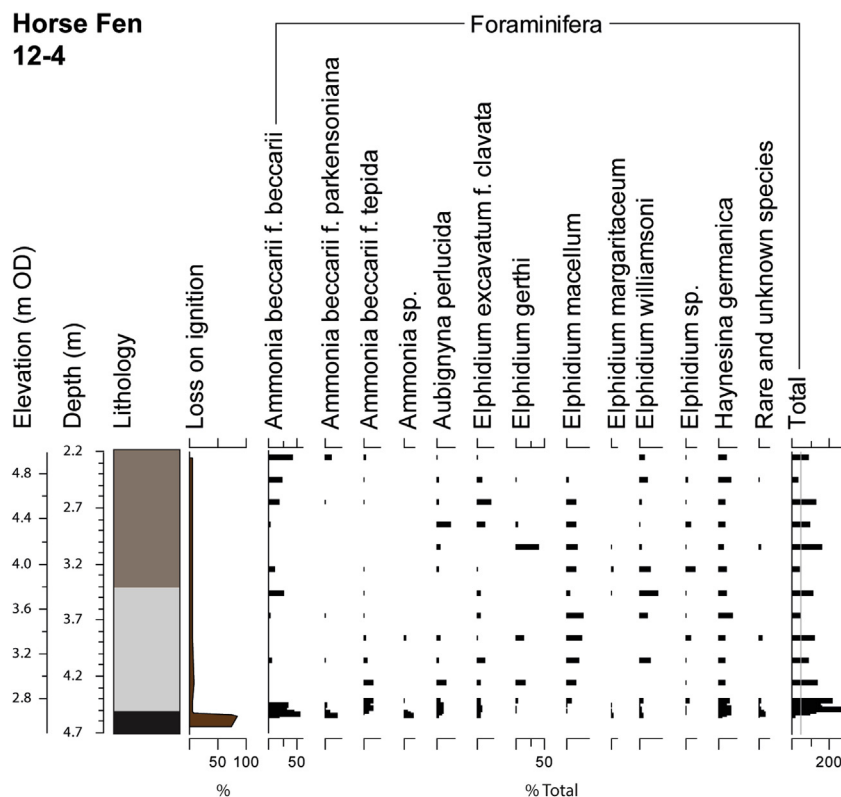


Fig. 10. Horse Fen 12-4 litho- and bio-stratigraphy. Foraminifera >5% of total tests counted (grey line n = 50). Lithology key same as Fig. 6. Pollen for this location in Stevens (1959) though exact elevations do not match.

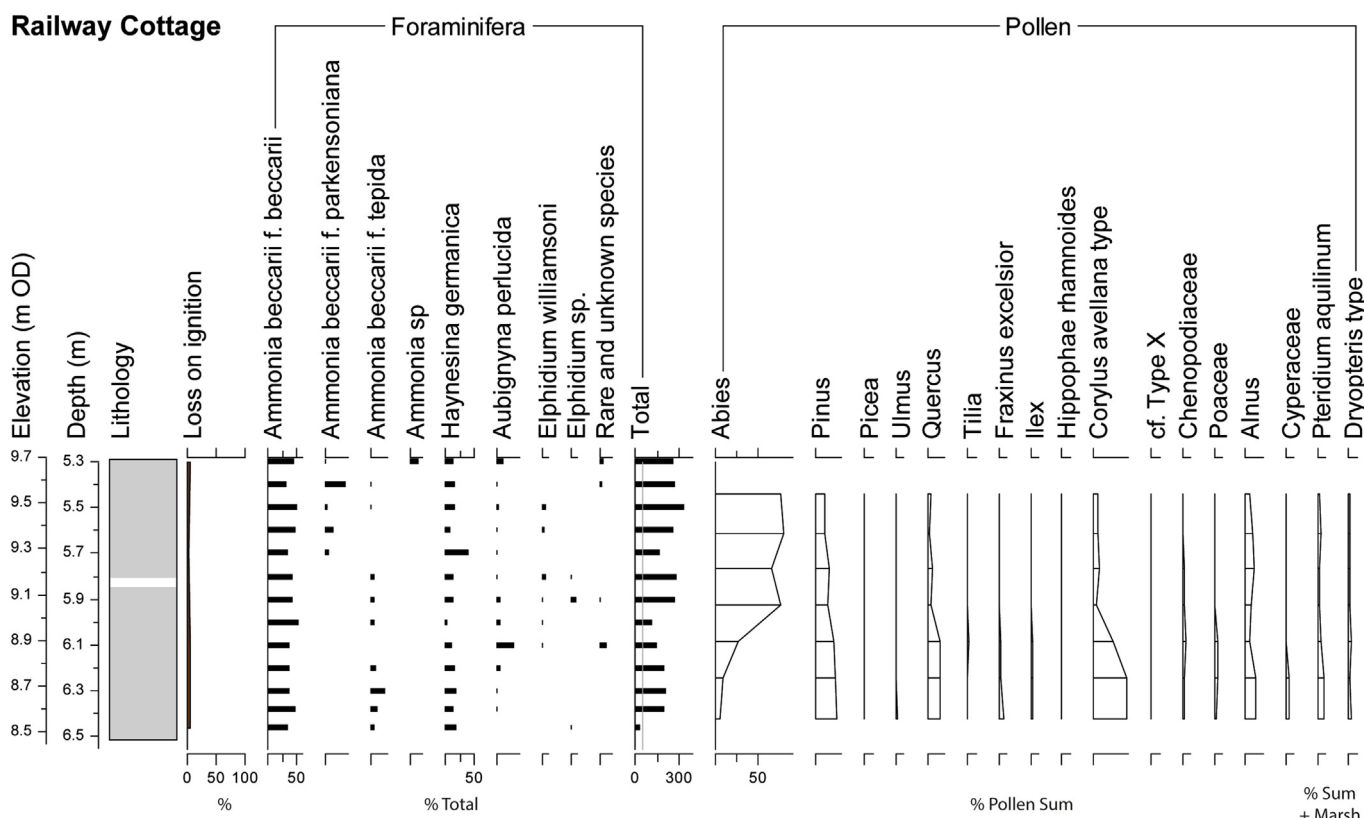


Fig. 11. Railway Cottage litho- and bio-stratigraphy. Foraminifera >5% of total tests counted (grey line $n = 50$). Selected pollen taxa shown. Lithology key same as Fig. 6.

other pollen as well as indicating the increasing ecological importance of fir growing in proximity to the site.

5.6. Bradmoor Hill

Stevens (1959) reports the highest occurrence of the Nar Valley Clay at Narford Hall at ~19 m OD, although without a sediment description. Our borehole at Bradmoor Hill (52.70314, 0.60444) is ~1.3 km north of this site, in a small pit on the edge of Bradmoor Plantation. At the base of our borehole at 8.87 m (9.24 m OD) to 8.15 m, there is a silty sand with occasional chalk fragments (Fig. 6). Overlying this to 6.41 m is a grey silty clay with small chalk fragments and thin laminae of fine sand, with occasional traces of detrital organic material. From 6.15 to 4.38 m (6.15–6.41 m was not recorded) is a laminated coarse-fine silty sand with occasional fine chalk fragments. Above 4.38 m the silt-clay content of the sand increases to 2.8 m from where clay-silt containing many shells of *Ostrea edulis*, *Hydrobia* and *Littorina* extends to ~0.50 m below the ground surface (organic content of the clay-silt is typically less than 10%).

The deepest occurrence of foraminifera at Bradmoor Hill is at 3.80 m (Fig. 12), with samples at approximately 1 m intervals below this level barren of tests. From 3.80 to 2.55 m forms of *A. beccarii* and *H. germanica* dominate with some *A. perlucida*. Above 2.80 to 0.20 m *A. perlucida* decrease with an increase in *E. williamsoni*. This is a gradual change with no rapid switches in assemblage, except for a spike in an unknown *Elphidium* sp. at 2.55 m. This entire assemblage is indicative of a stable intertidal environment.

The pollen spectra from Bradmoor Hill are largely homogeneous throughout, although there are some changes between the lower clay and the upper sandy-silt facies (Fig. 12). The sequence is dominated by *Abies*, which attains high values (to 90%) with smaller

numbers of other coniferales, including, especially *Pinus* and *Picea*. Both are consistent at low levels through most of the profile and expand in the upper sandy-silt from c. 0.4 m. Other coniferales include sporadic occurrences of *Taxus* and Cupressaceae indet. Deciduous trees include small but consistent levels of *Quercus* (to 4%) and *Alnus* (peak to 8%). Thermophiles occur sporadically with *Carpinus*, *Tilia*, *Fraxinus*, *Ilex* and notably *Pterocarya* in the upper levels. Type X is noted and small numbers of Vitaceae are present in the lower clay-silt. Ericales show some increase from 0.4 m. Although not present in quantity, there is a diverse range of herb pollen. Poaceae and Cyperaceae become more important in the uppermost sample. There are substantial numbers of Dinoflagellates.

This pollen sequence clearly shows the dominance of *Abies* on, or in very close proximity to the site (Fig. 12). The importance of *Abies* and the presence of Type X, *Pterocarya* and Vitaceae (West, 1956), when compared with Marks Tey (Turner, 1970), suggests an immediate post-temperate phase (HoIV). Thermophiles are more frequent in the lower part of the profile (below ~1.80 m) and this suggests the remaining vegetation of the late temperate (HoIII), which fits with Stevens (1959) assessment of the nearby Summer End Farm borehole. It should be noted that the dominance of *Abies*, which was growing in close proximity and with high pollen values, will have suppressed the importance of other taxa. Changes in the upper levels of the profile (the sandy-silt from ~0.4 m) may indicate further climatic change or increasing soil acidity in response to pedogenic change caused by the dominance of *Abies*. More acidophilous taxa include *Pinus*, *Picea* and Ericales.

5.7. Chronology

The pollen results demonstrate the correlation of the Nar Valley

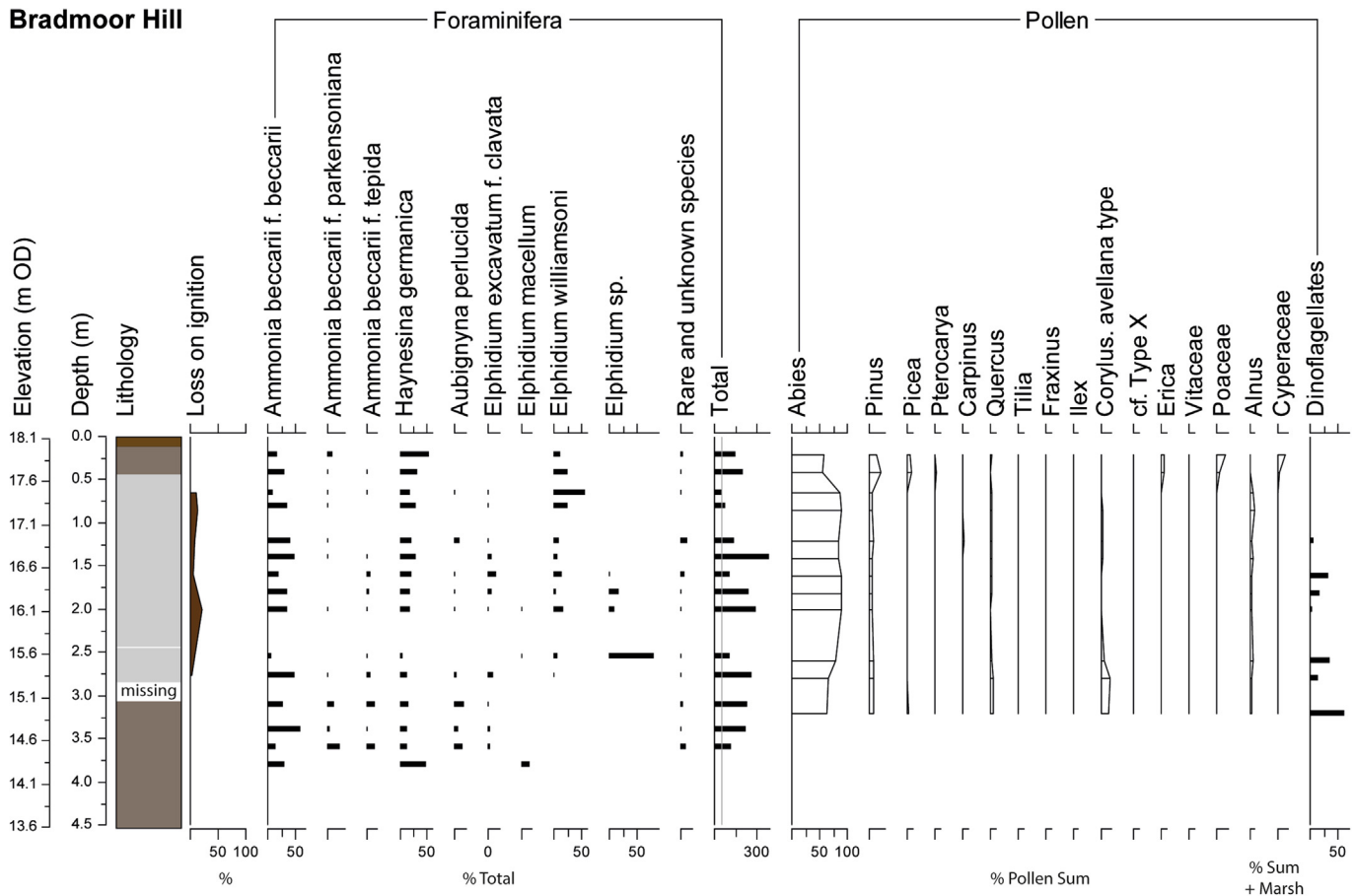


Fig. 12. Bradmoor Hill litho- and bio-stratigraphy. Foraminifera >5% of total tests counted (grey line $n = 50$). Selected pollen taxa shown. Lithology key same as Fig. 6.

sequences with the known Hoxnian pollen-assemblages (Table 1), but as discussed above, relating this to the marine oxygen isotope framework to compare the results on a broader scale is a challenge (Thomas, 2001). As result, we applied an independent chronological control for the timing of the deposition of the freshwater deposits found at the lower sites. Material collected in this project did not yield many *Bithynia* opercula (material was only found at Tottenhill and one fragment from Horse Fen), which have been successfully used elsewhere in relative AAR dating of the British Quaternary (Penkman et al., 2013).

We compare the Tottenhill and Horse Fen opercula dataset (Fig. 13 and supplementary information) to the range of data for British sites (Penkman et al., 2011, 2013). The preparation technique of sample bleaching removes the leachable, open-system matrix of shell protein, leaving a component that exhibits closed-system behaviour (the 'intra-crystalline' fraction). The protein degradation in this intra-crystalline fraction is therefore dependent only on time and temperature (Penkman et al., 2008), enabling aminostratigraphic correlation between sites sharing an equivalent integrated temperature history (Wehmiller et al., 1992, 2000). The DL ratios of aspartic acid/asparagine, glutamic acid/glutamine, serine, alanine and valine (D/L Asx, Glx, Ser, Ala, Val) as well as the [Ser]/[Ala] value are assessed to provide an overall estimate of intra-crystalline protein decomposition (IcPD). In a closed system, the amino acid ratios of the FAA and the THAA subsamples should be highly correlated, enabling the recognition of compromised samples (e.g., Preece and Penkman, 2005). The D/L of an amino acid will increase with increasing time, but each amino acid racemises at a different rate (e.g., Kaufman, 2006), due to differing side chains as

well as stabilities in peptide bonds. This means that they are useful over different timescales, with fast racemisers such as Asx allowing better temporal resolution at young sites (less than ~130 ka in the UK; Penkman et al., 2013), but at older sites, where its values approach equilibrium, the extent of natural variability within the data precludes further age discrimination. Conversely, Val allows only relatively poor age resolution in young contexts but provides much better temporal resolution at older ones, back to the Pliocene (Penkman et al., 2011). Serine is one of the most geochemically unstable amino acids, producing alanine as one of its decomposition products (Bada et al., 1978). The ratio of the concentration of serine ([Ser]) to the concentration of alanine ([Ala]) therefore gives a useful indication of the extent of protein decomposition within a closed-system, with [Ser]/[Ala] decreasing with time. The D/L of Ser is less useful as a geochronological tool for samples of this age, but is presented here as aberrant values are useful indications of contamination.

Many attempts have been made to refine the temporal resolution of AAR and generate numerical dates from kinetic experimental data (see Clarke and Murray-Wallace (2006) for a review), but recent studies have shown that high temperature kinetic experiments may not accurately mimic low temperature protein diagenesis in some biominerals (Demarchi et al., 2013; Tomiak et al., 2013). This 'calibration' approach has therefore not been attempted in this study, but the data has been compared to the range of data for British sites (Penkman et al., 2011, 2013), which (ignoring urban heat effects) span a narrow range of mean annual temperature (MAT) of 9–10 °C (Penkman et al., 2013), so it is assumed that the samples will have experienced similar integrated

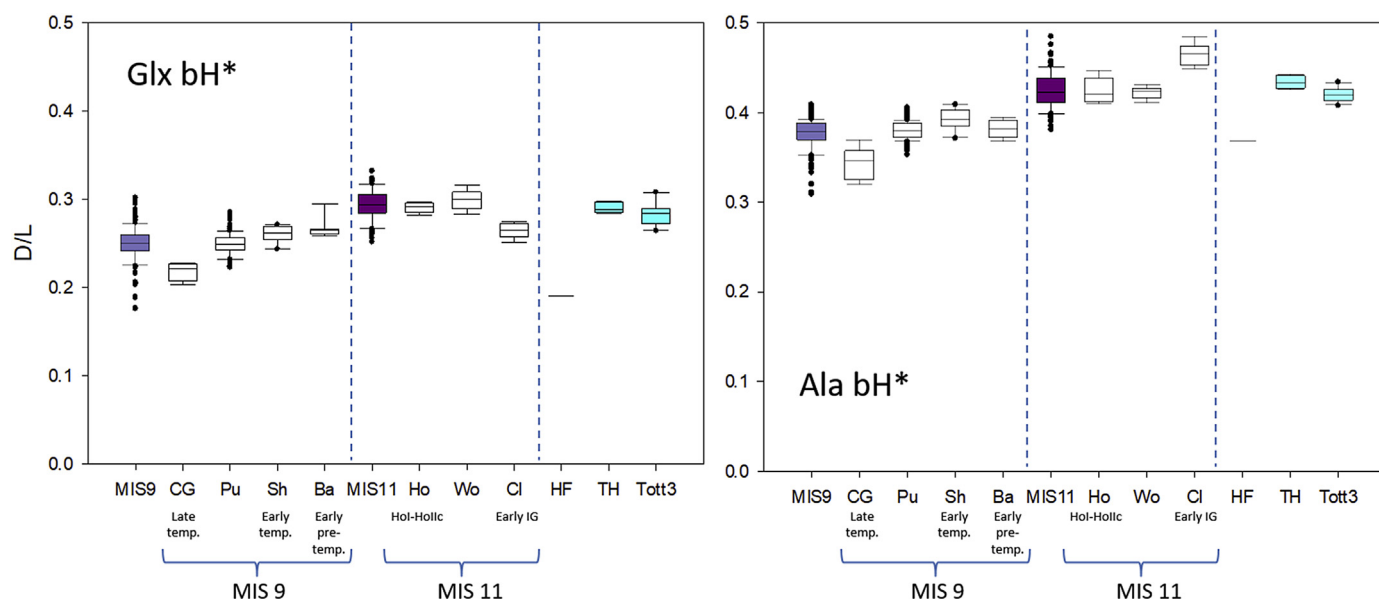


Fig. 13. D/L values of glutamic acid/glutamine (Glx) and alanine (Ala) for the total hydrolysable amino acid (THAA; H) fractions of bleached *Bithynia tentaculata* opercula from Horse Fen (HF) and Tottenhill (TH and Tott3) (light blue) compared with opercula from UK sites correlated with MIS 9 (grouped in darker blue) and MIS 11 (grouped in purple). Selected relevant sites are plotted in the order in which they are presumed to occur based on the pollen succession (CG = Cudmore Grove, Pu = Purfleet, Sh = Shoeburyness, Ba = Barling, Ho = Hoxne, Wo = Woodston, Cl = Clacton) by which to compare the results from this study. For each group, the base of the box indicates the 25th percentile, the line within the box plots the median, and the top of the box indicates the 75th percentile. Where more than nine data points are available, the 10th and 90th percentiles can be calculated (shown by lines at the bottom and the top of the boxes, respectively). The results of each duplicate analysis are included in order to provide statistically significant sample sizes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thermal histories. As amino acid racemization rates within biominerals are dependent on the underlying protein sequence (the ordering of the amino acids in the peptide chain), significant differences are observed in the rates and extent of racemization between different species, the so-called “species effect” (Lajoie et al., 1980; Miller and Hare, 1975; Penkman et al., 2007). This can be ignored in this study, as all the analyses and comparator material are undertaken on *Bithynia* opercula which have been shown to show only minimal differences in racemization within the genus (Penkman et al., 2013).

The “chalky” opercula, which appear to have undergone mineral diagenesis, show greater variability than the normal opercula from the same horizon, and are therefore not included in the results in Fig. 13 for the age estimation. The Tottenhill samples show levels of protein breakdown consistent with either a mid-late MIS 11 age, or possibly, early MIS 9. As so little decomposition occurs in the cold stages and because of the extent of natural variability in biological samples, it can be difficult to discriminate the end of one warm stage from the beginning of the next (Penkman et al., 2013). The operculum AAR sample from Horse Fen 13-1 shows lower levels of protein breakdown than at Tottenhill (Fig. 13) but, as this is based on a fragmentary sample with low concentrations, this should be treated with caution.

In an attempt to refine the age further, the AAR data can be examined for relevant sites plotted in order of the pollen succession where the data is available from the relevant horizons (Fig. 13). Within MIS 9: Cudmore Grove, late temperate (Roe et al., 2009); Shoeburyness, early temperate Hol/II (Roe et al., 2011); Barling early pre-temperate (Bridgland et al., 2001); within MIS 11: Hoxne Stratum E (Hol-Holc) (Ashton et al., 2008); Clacton early interglacial (Bridgland et al., 1999). Based solely on these comparisons, the Tottenhill samples are consistent with an MIS 11 age, and less likely to correlate with MIS 9, but this cannot be excluded.

The lack of further material for AAR dating and a lack of independent dating of the marine sediments means we are reliant on

correlation with published sites of known ages and additional stratigraphic evidence. Both Bradmoor Hill and Railway Cottage, which do not have evidence of the Nar Valley Freshwater Beds, as well as Stevens (1959) Summer End Farm site at a similar elevation, are typified by very high percentage of *Abies*, diagnostic of HolIII. In Stevens (1959) East Winch borehole, the *Abies* content is lower (<10%), suggesting its deposition during early HolIIIa. The dominance of fir is also found at Marks Tey (Turner, 1970), Inner Silver Pit (Scourse et al., 1998), Hoxne (West, 1956), Clacton (Pike and Godwin, 1952) and East Hyde, Tillingham (Roe, 2001), which through independent means have all been correlated with MIS 11 (Ashton et al., 2008; Bridgland et al., 1999; Rowe et al., 1999; Scourse et al., 1998; White et al., 2013). Together, these sites account for most of the Hoxnian sites at which the late part of the interglacial is represented palynologically. The exception is the fluvial-estuarine record at Woodston, Peterborough which, with low *Abies* values, has been correlated to HolIIc (Horton et al., 1992) but independently dated using AAR to MIS 11 (Penkman et al., 2013). However, the presence of marine clay overlying glacial sediments at Bradmoor Hill and expected to be at the base of Stevens' (1959) East Winch and Summer End Farm sites and our Railway Cottage borehole, which are most likely from the extensive MIS 12 Anglian glaciation (Pawley et al., 2008), leads us to conclude that the marine sedimentation in the higher-level Nar Valley interglacial sites relates to a MIS 11 transgression during the late-temperate phase of the interglacial, most probably the warm MIS 11c substage (Candy et al., 2014).

The apparent of the Nar Valley Freshwater Beds above ~4 m OD and the difference in relative timing (c. HolI versus HolII) of the marine phases between the lower and upper sites, raises the question of whether there are two separate phases of marine sedimentation recorded in the Nar Valley. Previous dating of both the Nar Valley Freshwater Beds and Nar Valley Clay at Tottenhill suggested correlation with MIS 9 (Rowe et al., 1997; Scourse et al., 1999). Our new AAR results from freshwater *Bithynia* opercula at

Tottenham point to late MIS 11 age, but cannot also exclude an early MIS 9 age (Fig. 13), with the pre- and early-temperate (Hol-II) pollen assemblage for the Freshwater Beds at Tottenham (Ventris, 1996) potentially favouring the early MIS 9 age, with the pollen not suggesting late interglacial conditions. The absence or relatively low abundance of *Abies* at Horse Fen, Tottenham and Blackborough leads to the suggestion of a difference in the regional pollen assemblage in comparison with MIS 11 sites in eastern England where *Abies* is dominant. The absence of 'classic' Hoxnian pollen indicators for the early and late temperate phases: *Pterocarya*, *Vitis*, *Buxus*, *Azolla filiculoides* and the low levels of *Taxus* at Horse Fen and Tottenham, (albeit with the presence of Type X demonstrably present in both the MIS 11 and MIS 9 interglacials (Roe et al., 2009)), also highlights that these sites may have been deposited during a different, post-Hoxnian interglacial stage. These species, as well as Type X, are also absent at Blackborough Quarry (potentially due to poor pollen preservation) and mean that it is not possible to designate with any certainty the interglacial stage to which this particular sequence might belong. These lower-level Nar Valley profiles show similarity with estuarine sites from the Thames and Essex with low *Abies*, high *Pinus* and occasional Type X, including Barling (Bridgland et al., 2001), Purfleet (Bridgland et al., 2013; Schreve et al., 2002), Cudmore Grove (Roe et al., 2009), Shoeburyness (Roe et al., 2011), Rochford and Burnham-on-Crouch (Roe and Preece, 2011) all of which have been attributed to MIS 9. In the absence of absolute dating, it is therefore not possible to reject a MIS 9 age for the lower Nar Valley sites, as also dated by Scourse et al. (1999) at Tottenham. This contrasts the more definitive attribution of the upper sites to MIS 11. Therefore, the Nar Valley Clay, previously recorded as being a single unit (Stevens, 1959; Ventris, 1996), most likely represents two separate periods of marine inundation, during two different interglacials.

6. Discussion

6.1. Modes of sea-level change in the Nar Valley

The results presented above provide details of a lower freshwater peat, transgressed by a marine clay, most likely deposited during MIS 9. In the uppermost sites (Railway Cottage and Bradmoor Hill) the peat is absent (Fig. 6), with the marine clay overlying a silty clay with sand and chalk fragments, devoid of foraminifera. It is most likely that the underlying sandy-silt is glacially derived, probably correlating with the Anglian (MIS 12) deposits found along the East Anglian coast (Pawley et al., 2008; Jim Rose, personal communication), which means the upper Nar Valley Clay was most likely deposited earlier (during MIS 11) than that found in the lower sites. We summarise the palaeo-environments of peat and clay recorded in our new boreholes in Table 2, and synthesize the results to assess the mode of sea-level change through the sequences: gradual versus abrupt.

6.1.1. Change in tendency

The tendency of a sea-level indicator describes the increase or decrease in marine influence (Shennan et al., 2015; van de Plassche, 1986). Foraminifera are absent above the limit of the highest astronomical tides, but occur throughout the marine environment (Fig. 3). The replacement of freshwater peats, devoid of foraminifera, by clay containing taxa such as forms of *Ammonia beccarii*, *Haynesina germanica* and *Elphidium* species at Horse Fen and Blackborough End Quarry records a positive tendency across the peat-clay (transgressive) contact. Our new section at Tottenham Quarry does not extend into the marine shell-bearing clay recorded by Ventris (1996), with the sequence truncated by the quarry excavations and only extending into the freshwater lake marl above

the peat. The composite section of Ventris (1996) from the northern half of the quarry suggests that the freshwater lake was replaced by brackish conditions (as indicated by the presence of *Hydrobia* molluscs), followed by fully marine conditions (indicated by the occurrence of oysters). This site also records an increase in marine influence and, therefore, a positive sea-level tendency.

At Railway Cottage, the foraminifera-containing clay overlies gravel clasts, mainly flints (of unknown origin) suggesting a stable marine environment but no indication of a change in tendency. At Bradmoor Hill, the first occurrence of foraminifera (at ~3.8 m) occurs in clay in association with occasional fragments of chalk and flint, although these clasts disappear with the slight increase in organic content above ~3.0 m. There is then some reworking between the glacial sediments and the bottom of the overlying marine clay. Therefore, it is not possible to ascribe a change in tendency based on the coastal succession model in Fig. 3 for the upper sites, although it appears marine conditions replaces non-marine glacial sediments. Evidence of negative sea-level tendencies within the Nar Valley interglacial sequences is absent as there are no intercalated peats within the Nar Valley Clay recorded by this and previous work (Stevens, 1959; Ventris, 1996).

6.1.2. The nature of the transgressive contact: abrupt or gradual?

The lower sites (Horse Fen, Blackborough End Quarry and Tottenham Quarry) all provide evidence of a positive sea-level tendency. As discussed above, there is no direct evidence for a change in tendency over a transgressive contact at Bradmoor Hill or Railway Cottage. In both cases, however, the relatively homogenous foraminiferal assemblages of forms of *A. beccarii* f., *H. germanica* and species of *Elphidium* suggest a stable intertidal to subtidal environment with no evidence for rapid change in water depth. The occurrence of beds of molluscs such as *Hydrobia*, *Littorina* and oysters also suggests no rapid changes in environment.

Previous work in the Nar Valley has not focused on the nature of the peat-clay transition and our detailed laboratory analysis allows assessment of the character of the transgressive contact using the coastal succession model in Fig. 3. We found very low numbers of typical salt-marsh foraminifera such as *Jadammina macrescens* and *Trochammina inflata* within the analysed Nar Valley sequences, nor are there transitional salt-marsh pollen taxa. The transgressive overlaps at Horse Fen, Blackborough End Quarry and Tottenham Quarry record a freshwater peat replaced by low intertidal facies, representative of a fen being replaced by a tidal flat. Salt-marsh facies are absent, so the transgression can arguably be interpreted as a 'moderate' drowning, a transition from zone 2 to zone 4 in Fig. 3. Using modern analogues this represents a minimum RSL rise of about half the tidal range, as peat forms above the highest tide level and the salt marsh to mudflat transition is found around mean tide level in the UK (e.g., Horton and Edwards, 2006). Is this evidence for a rapid rise in sea level?

We compare our lower Nar Valley stratigraphies with similar sequences from Holocene estuarine deposits from this region. This is potentially a useful exercise, because we know that during the Holocene, very rapid sea-level oscillations (on the order of metres per century) did not occur (with the exception of the 8.2 ka BP event (Lawrence et al., 2016)). If the transgressive sequences we find in the Nar Valley also occur in the Holocene, then we may reject the hypothesis that they are due to rapid sea-level rise and ice-sheet instability. Holocene transgressive sequences in eastern England that include the same, non-erosive, transition from fen to tidal flat include several deep cores along the Norfolk coast, where basal peats are overlain by mudflat sediments (Andrews et al., 2000). Dates on these contacts range between 5000 and 7000 cal yr BP when relative sea level rose at average rates of ca. 3–5 mm/yr (Shennan et al., 2000).

Table 2
Summary of palaeoenvironments and estimate of age at each core location in the Nar Valley from this study, along with an estimate of the change recorded with respect to the coastal succession model in Fig. 3. *The balance of evidence points to a MIS 9 age for these sites, but a MIS 11 age can also not be rejected outright.

Site	Peat-clay contact elevation (m OD)	Foraminifera palaeo-environment	Pollen palaeo-environment	Relative timing of marine conditions (Hoxnian pollen stage)	Change in tendency	Change in coastal zone (from Fig. 3)	AAR result	Suggested MIS age correlation
Bradmoor Hill	13.9 (first occurrence of foraminifera)	Stable intertidal	Succession from late-temperate to post-temperate woodland	HolIb potentially to start of HoIV	None	Zone 4/5 Stable marine conditions	n/a	11
Railway Cottage	6.5 (onto hard substrate)	Stable subtidal	Succession from deciduous woodland to late-temperate woodland	End of HolIa to HolIb	None	Zone 4/5 Stable marine conditions	n/a	11
Horse Fen (12–4)	2.8	Intertidal, deepening to shallow subtidal	Succession from fen to alder carr and aboreal woodland (from Stevens, 1959)	HolId (from Stevens, 1959)	+	Change from zone 2 to 4 (RSL rise=half the tidal range)	n/a	9 (11)*
Tottenham Quarry	~2.6 m (from Ventris, 1996)	No foraminifera present in this study	Late early-temperate woodland	HolIc (from Ventris, 1996)	None in this study + in Ventris (1996)	Gradual (from Ventris, 1996)	Late MIS 11 or early MIS 9 (Bithynia opercula)	9 (11)*
Blackborough End Quarry	~1.1	Intertidal/shallow subtidal	Succession from early temperate to temperate woodland	Holla-c ?	+	Change from zone 2 to 4 (RSL rise=half the tidal range)	n/a	9 (11)* ?
Horse Fen (13–1)	~2.3	Intertidal, deepening to subtidal	Succession from fen to alder carr and aboreal woodland	HolIc or HolId	+	Change from zone 2 to 4 (RSL rise=half the tidal range)	Mid-Pleistocene (Bithynia opercula)	9 (11)*

The Fenland arguably represents the nearest Holocene analogue to the estuary of the Nar Valley during MIS 11 and 9. In the Fenland, several basal peat sequences representing a fresh-water swamp environment are overlain by either salt-marsh or mudflat sediments. Examples of the latter are described by Waller (1994) at Welney Washes (ca. 6200 ¹⁴C yr BP), Feltwell Common (ca. 4200 ¹⁴C yr BP), and Farcet Fen (ca. 3800 ¹⁴C yr BP). Relative sea-level rise during the formation of these contacts was on average ca. 3 mm/yr (Shennan, 1994). Rapid compaction of peat following marine inundation can also create accommodation space that results in widespread inundation and the rapid deposition of thick intertidal sediments (Long et al., 2006).

In summary, several examples exist from Holocene coastal sequences in eastern England that include similar stratigraphic signatures of the drowning of basal peat as found in the lower Nar Valley. These transitions were not due to rapid rates of sea-level rise caused by abrupt ice-sheet collapse. Instead, they can be formed by gradual changes in RSL due to long-term subsidence, or to various coastal processes, including coastal barrier shifts, changes in basin morphology and local tidal range, basal peat compaction, and sedimentation (Shennan, 1994). Our model of rapid sea-level rise (Fig. 3B) does not apply to the Nar Valley sequences, but rather suggests the sea-level rise recorded in the lower (MIS 9) sites was gradual.

6.1.3. Lateral extent of the transgressive contact and its representation in adjacent sequences

The occurrence of a transgressive contact over a wide area of the Nar Valley (Fig. 6) suggests the marine sedimentation was not simply a consequence of site-specific processes. Transgressive contacts from the same time period which are recorded in multiple cores may suggest a regional tendency (Shennan et al., 2015). Based upon the Hoxnian-type pollen zones (Table 1), the transgression at Horse Fen and Tottenham Quarry occurred within HolI, most likely HolIc at Horse Fen 13-1 and Tottenham, and HolId at the upper Horse Fen sites, suggesting a system-wide positive tendency. The difference in Hoxnian pollen-zone between Horse Fen 13-1 (HolIc) and 12-4 (HolId) may be a consequence of the ~5 m difference in elevation, suggesting that the sea-level rise was gradual during this phase of climatic succession. The pollen assemblage at Blackborough End Quarry similarly suggests that the transgression occurred during the latter part of the Early Temperate phase, as in Horse Fen and Tottenham, but with the absence of diagnostic Hoxnian taxa as found at the other sites, correlation remains tentative.

The relative timing of the marine conditions at the higher sites of Railway Cottage and Bradmoor Hill differs from the lower transgressive contacts, with both containing HolIII (and potentially early HoIV at Bradmoor Hill) pollen assemblages. This fits with the Ventris (1996) summary of HolIIIb marine conditions at East Winch (~8.5 m OD) and Summer End Farm (Stevens, 1959) (~12.8–10.5 m OD). The absence of marine conditions during HolIII in the lower-level sites, based upon the argument that the two phases of marine sedimentation occurred during two separate interglacials.

The representation of a positive tendency across a peat-clay contact may also be replicated in adjacent vertically deeper sequences as a deepening, for example from an intertidal to subtidal foraminiferal assemblage. The transgressive contact at Blackborough End Quarry (~1.1 m OD) and the marine clay of Horse Fen 13-1 are the only instance from the cores we collected where there is an elevation overlap of this nature. At this elevation of the Blackborough End Quarry flooding surface, the Horse Fen clay contains a homogenous foraminiferal assemblage

dominated by forms of *A. beccarii* and *Aubignyna perlucida*, suggesting stable shallow subtidal conditions, with no evidence for rapid deepening. The transgressive contact at Horse Fen 13-1 (~2.3 m OD) overlaps with diatom samples analysed in the upper part of the Manor Farm borehole by Mitlehner (1992), which also show no rapid changes in water depth, but instead a gradual shift in current turbidity in a shallow marine setting.

Consideration of the palaeo-stratigraphic evidence from the Nar Valley against the three main criteria leads us to conclude that the mode of sea-level change during the Nar Valley interglacial sequence was gradual (Fig. 14), in line with similar Holocene changes, with potentially regional transgression occurring during both MIS 11 and 9.

6.2. Sea-level change in the Nar Valley

Pollen data from the Nar Valley sequences correlate with the British Hoxnian interglacial pollen assemblage *sensu lato* (Table 1), which have been demonstrated to have affinities to both MIS 11 and 9 (Thomas, 2001), although the stratotype site of Hoxne and the full Hoxnian para-type succession at Marks Tey are now correlated with MIS 11, probably substage 11c (Ashton et al., 2008; Candy et al., 2014; Rowe et al., 1999). The balance of evidence (discussed above) leads us to suggest the Nar Valley Clay was deposited during both MIS 11 and 9, with long-term uplift (Westaway, 2009) separating their local elevation (Fig. 14), and not during a single interglacial as previously thought (Stevens, 1959; Ventris, 1996). The two-interglacial model further supports evidence for the mode of sea-level change in the Nar Valley being gradual, with rising sea level during MIS 9, and a stable highstand recorded during both MIS 11 and 9 (Fig. 14), rather than the elevation difference between the lower and upper sites being explained by a sea-level jump. However, we cannot preclude erosion by subsequent glacial sedimentation of the upper part of the marine sediments in the lower sites (Horse Fen, Tottenhill and Blackborough) where Holli pollen is absent. This means it is also not possible to reject outright a MIS 11 age for the whole Nar Valley sequence based upon correlation with the Hoxnian succession at Marks Tey (Rowe et al., 1999; Turner, 1970). Nonetheless, even within a single interglacial framework there is a lack of indicators for rapid sea-level oscillations in the Nar Valley.

6.3. MIS 11 and MIS 9 sea-level highstands around the world

Evidence for two late-Middle Pleistocene marine transgressions (MIS 11 and 9) have been found elsewhere in eastern England, most

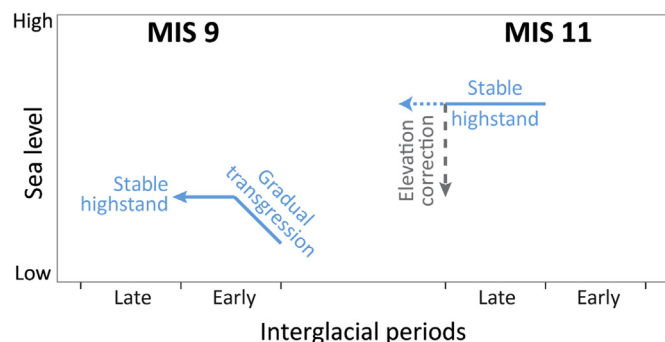


Fig. 14. Summary figure as to the mode of sea-level change in Nar Valley assuming the two sequences (upper and lower) were deposited during differing interglacials. The alternative hypothesis is that the lower sites (shown as MIS 9 here) were also deposited during MIS 11, but during a differing sub-stage. Elevation correction is for illustration assuming uplift between MIS 11 and 9 (Westaway (2009) estimates ~3.3–5 m uplift during the two interglacials in this location).

notably in the channel-fill deposits of the Thames and its tributaries in eastern Essex (Roe and Preece, 2011). Determining maximum water heights at any of these sites, or in the Nar Valley, is difficult as ascribing absolute water depths from the foraminiferal assemblages is not possible and the upper surfaces of the marine units have been eroded. Furthermore, regional uplift and cycles of glacial isostatic adjustment have modified the elevation of the sediments from that at the time of deposition (Westaway, 2009). Due to the issues of dating 'Hoxnian' sediments, as discussed here, correlation with other sites in northwest Europe is challenging and beyond the scope of this study. However, the absence of intercalated peats within the interglacial marine sediments, or any change in tendency (beyond the initial recorded transgression at both MIS 11 and 9 sites in eastern England such as Cudmore Grove, Tillingham, Shoburness and Barling (Bridgland et al., 2001; Roe et al., 2009, 2011; Roe and Preece, 2011)), suggests that neither highstand was typified by markedly rapid RSL changes.

Geomorphological evidence of MIS 11 and 9 sea level found in low-latitude regions provide a snapshot of the interglacial sea-level highstand at, or above, present sea level (Blakemore et al., 2015; Chen et al., 2014; Hearty and Kindler, 1995; Murray-Wallace, 2002; Raymo and Mitrovica, 2012; Schellmann and Radtke, 2004; Vezina et al., 1999). A stack of ocean sediment core-based reconstructions of Late Pleistocene sea level identifies the highstands in sea level during MIS 11 and 9, but is unable to resolve millennial-scale structure (Spratt and Lisiecki, 2016). The only 'continuous' sea-level record that might provide further insight into the mode of sea-level change during the MIS 11 and 9 highstands is currently from the Red Sea which, within the sample resolution, does not suggest any rapid fluctuations when sea level is above present (Rohling et al., 2009, 2010), unlike the MIS 5e record in the same location (Rohling et al., 2008).

Ice extent during MIS 9 has received little attention (Past Interglacials working group of PAGES, 2016) and, a mean highstand of 9 ± 23 m based upon a range of ocean-core records (Spratt and Lisiecki, 2016), suggests the potential for either greater, the same or reduced total ice volume relative to present. Data for MIS 11 is a little more comprehensive. Ice core and oceanographic records from Greenland during MIS 11 suggest that although ice was probably present at the centre of the present ice sheet (Yau et al., 2016), it was much smaller in overall extent, potentially losing up to 6 m sea-level-equivalent volume (de Vernal and Hillaire-Marcel, 2008; Reyes et al., 2014). After correcting for GIA, Raymo and Mitrovica (2012) calculate that global mean sea level during MIS 11 was 6–13 m above present and infer melt of the Greenland and West Antarctic ice sheets towards the end of the interglacial, but relative stability of the East Antarctic Ice Sheet, although the rate of mass loss is unknown (Alley et al., 2010). Delayed melting of the ice sheets within MIS 11 fits with our pollen records from Bradmoor Hill and Railway Cottage, which suggest marine sediment deposition during the Late Temperate phase of the interglacial. Although there is clear evidence for sea-level highstands above present during MIS 11, and potentially also during MIS 9, in both the low latitudes and northwest Europe, the absence of indicators for one or more sea-level oscillations, in our albeit spatially limited datasets implies steady melt of the ice sheets during the interglacial phases.

7. Conclusions

MIS 11, 9 and 5e have been shown to be the warmest interglacials of the last 800,000 years (Past Interglacials working group of PAGES, 2016; Yin and Berger, 2012), and therefore hold insights into ice-sheet behaviour in warm climates and provide potential analogues for the future. Evidence for the mode of sea-level change during MIS 11 and 9 is sparse compared to that from

MIS 5e (Dutton et al., 2015). We present new detailed analysis of a 'Hoxnian' sequence from the Nar Valley and apply multi-proxy methods of reconstruction which have been widely applied to similar Holocene temperate-latitude estuarine sequences. Such records are valuable as they have the potential to provide more continuous archives of RSL change and therefore identify millennial-scale changes in sea level that large-scale geomorphological features, such as raised beaches, may not record. The application of methodologies developed in Holocene settings to previous interglacial deposits may be restricted by the preservation of material across a range of elevations, sampling resolution and limitations of dating. Notwithstanding these challenges, we apply the tendency methodology to marine sediments from over a ~20 m modern elevation range in the Nar Valley, with pollen analysis and AAR dating suggesting that there may be two periods of marine sediment deposition: one during MIS 11 (Hoxnian Late Temperate phase) from ~8 to 18 m OD; and a second phase potentially during MIS 9 (Hoxnian Early Temperate phase) from ~3 to 3 m OD, although we cannot conclusively preclude an alternative MIS 11 age for these lower sediments. It must be noted that these modern elevations likely bear very little resemblance to their elevation at the time of deposition due to glacial isostatic adjustment and long-term tectonic uplift. We do not find any compelling evidence for abrupt changes in sea level either in the Nar Valley or nearby similar sequences in eastern England during these times and no difference in the nature of the MIS 9/11 transgression when compared to similar Holocene sequences, where there is no evidence for abrupt (multi-meter) sea-level jumps. These results add weight to similar analysis of the MIS 5e record from the Netherlands (Long et al., 2015), which suggest gradual, rather than rapid, melt of the ice sheets persisted in these interglacials when sea level was at or above present-day levels, although much more data is needed to test these hypotheses.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.quascirev.2017.08.017>.

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